BELL & HOWELL SCHOOLS

DEVRY INSTITUTE OF TECHNOLOGY

ACTIVE AND PASSIVE COMPONENTS

COURSE 125

4-W

IMPORTANT NOTICE

This packet of lesson material contains a sheet which shows different styles of color-coded capacitors. Because of different surface finishes, paints, and manufacturing techniques, the color you see on actual color-coded capacitors may vary from that shown in this figure (Figure 30). On the other side of this sheet is Figure 31 which indicates in detail the meanings of the capacitor markings.

This sheet is located directly below this notice. You may want to display it for reference purposes or insert it into the lesson on capacitors. Notice that this sheet is Pages 45 and 46 of Lesson 1037, "CAPACITORS." Therefore, if placed in Lesson 1037, it should be placed just ahead of Page 47.

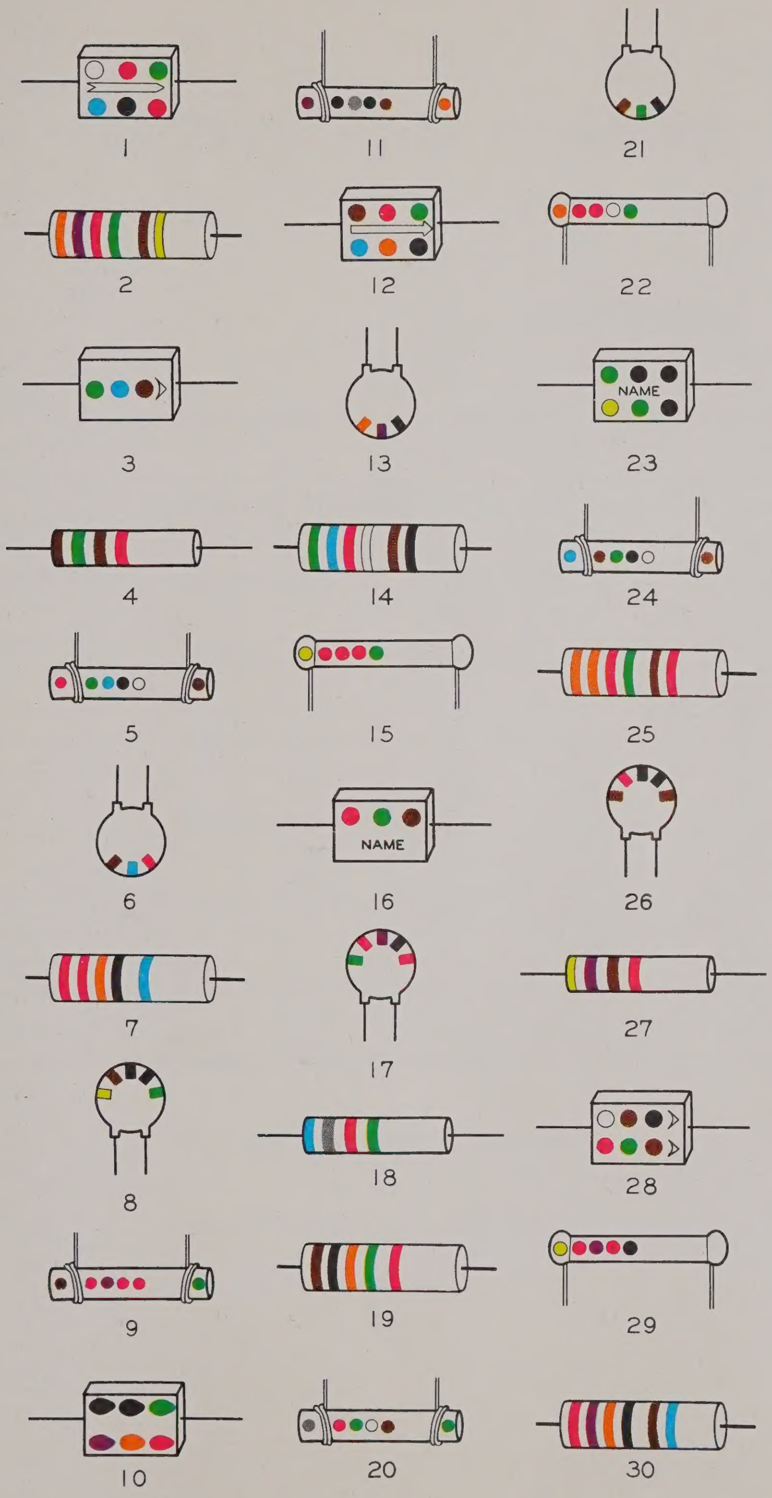
NAME
NAME

Figure 30

DIAGRAM NUMBER	CAPACITANCE (pF)	DC VOLTAGE RATING (VOLTS)	TOLERANCE RATING	TEMPERATURE COEFFICIENT (PPM / °C)	DOES CAPACITOR MEET *EIA* OR *JAN* REQUIREMENTS
1	2,500		20 %		*EIA*
2	3,700	1,400	5 %		
3	560	500	20 %		
4	150	500	2 %		
5	56	150	10 %	− 80	
6	1,600	500	20 %		
7	22,000	600	20 %		
8	10	500	.5 pF	− 220	
9	2,700	500	2 %	− 30	
10	500		3 %		*JAN*
11	8	350	.1 pF	− 750	
12	125	600	3 %		
13	37	500	20 %		
14	5,600	1,000	10 %		
15	2,200	600	5 %	− 220	
16	250	500	20 %		
17	27	500	2 %	− 330	
18	6,800	500	5 %		
19	10,000	200	5 %		
20	2.5	500	.1 pF	+ 30	
21	15	500	20 %		
22	2.2	600	.5 pF	− 150	
23	500	400	5 %		
24	15	150	10 %	− 470	
25	3,300	1,200	5 %		
26	20	500	1 %	− 30	
27	470	500	2 %		
28	100		5 %		*EIA*
29	2,700	600	20 %	− 220	
30	27,000	1,600	20 %		

Figure 31

ACTIVE AND PASSIVE COMPONENTS

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SEMICONDUCTOR AND VACUUM DIODES

1025

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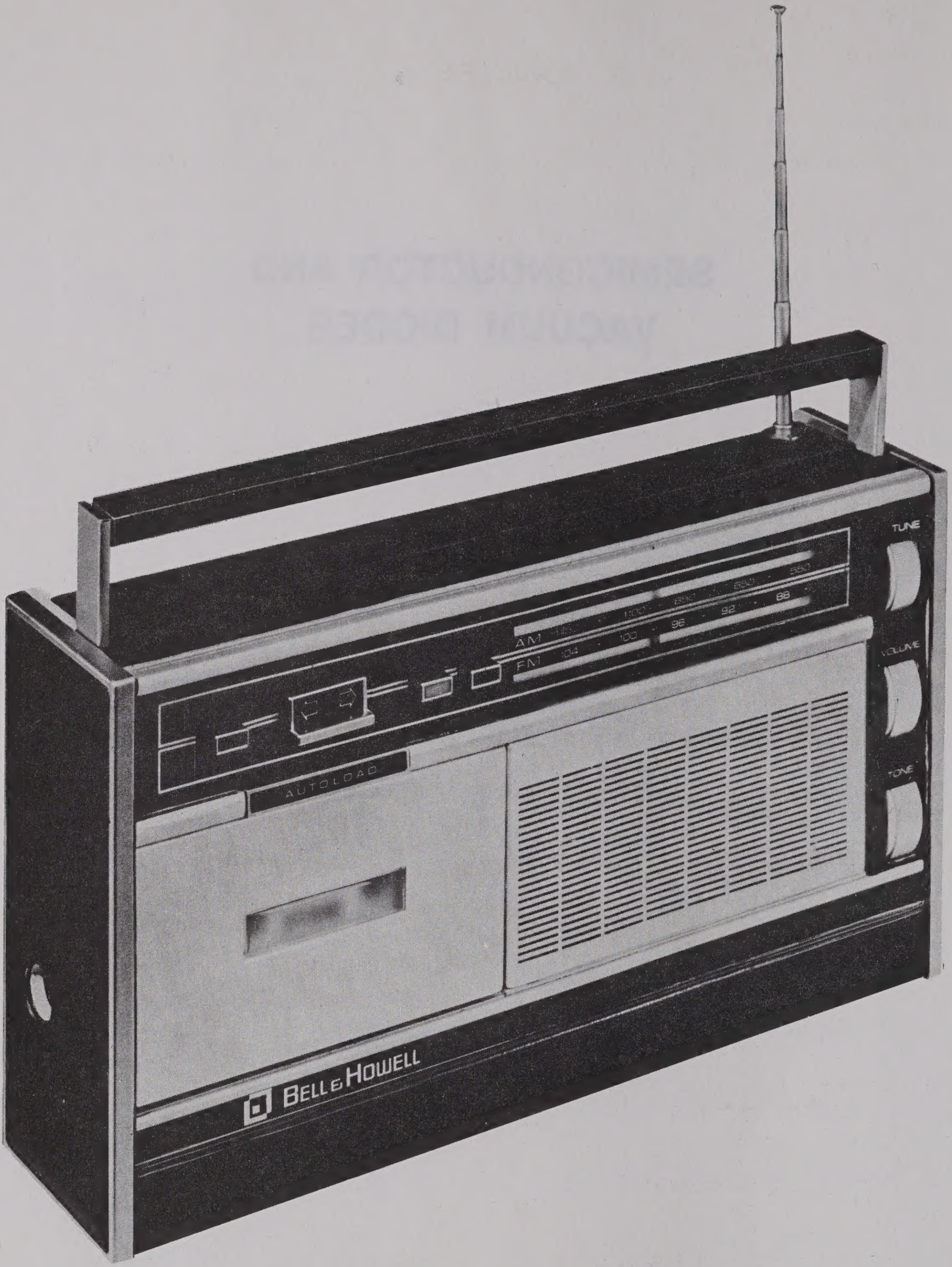

Many electronic units like this AM-FM Radio Recorder include a battery power supply for portable operation as well as an ac power supply. The ac power supply employs diodes to convert the line ac into dc for the unit.

Courtesy Bell & Howell

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> *Weakness does not prevent success if only the body is weak. The trouble in the average person is not lack of ability, intelligence, or health. It is lack of courage that comes from enthusiasm.*
>
> *—Arthur Brisbane*

SEMICONDUCTOR AND VACUUM DIODES

This lesson introduces the widely used devices called **DIODES**. The device's name comes from **DI** (meaning two) and **ODE** (from electrode). Originally, this name was formed to describe the construction of the first **ELECTRON TUBE** which contained two **ELECTRODES**; however, it is now also applied to **SEMICONDUCTOR** units that perform the same function as the diode tube.

The term "semiconductor," when linked with "diode," refers to a unit made by joining two different types of semiconductor material that do not conduct electrons as well as a true conductor, but do conduct better than an insulator. ("Semi" means half, so semiconductor is, literally, a "half conductor.") A conductor generally provides a very low resistance to conduction in either direction, but a semiconductor material exhibits a higher resistance to electron flow or conduction. The semiconductor material types are joined in a special way so that, when a proper polarity voltage is applied, electrons flow through both materials across the junction (where the materials join), but flow only very slightly in the opposite direction if the voltage is reversed.

An earlier lesson mentioned the different types of voltage sources: ac and dc. In ac, you will remember, the voltage changes and alternates polarity periodically, while in dc the polarity of the voltage doesn't change. AC voltages were also mentioned as being commonly available; almost all generating stations of electric utility companies in the U.S.A. supply ac power. Many other countries of the world also have ac power readily available, because ac can be distributed more efficiently than dc. However, electronic equipment frequently requires dc power for proper operation and, therefore, some method of converting ac to dc is necessary. This conversion of ac to dc is called **RECTIFICATION**, and the device that does the rectifying is called a **RECTIFIER**.

RECTIFIERS

The foundation on which the field of electronics is based is the control of electrons. One of the basic forms of electron control is the conversion of ac to dc, by which the alternating current is changed (or rectified) to direct current. In a rectifier, the electrons of an alternating current are prevented from reversing their direction of flow (changing their polarity) so that they flow in one direction only. Because semiconductor diodes and electron tube diodes both achieve this rectification action, they are both classed as rectifiers, even though they operate in somewhat different ways. The two terms, diode and rectifier, are often used interchangeably.

The semiconductor diode, as we have stated, used two types of conductive materials that readily pass electrons from one material to the other but strongly oppose any electron flow in the reverse direction. The electron tube diode has two metal objects, called electrodes, mounted in an airtight envelope. Through an arrangement of an electrical circuit, which will be explained more fully a little later in this lesson, electrons travel across the space separating one electrode from the other, but not in the reverse direction. In many electron tubes, the air is removed from inside the envelope, and these tubes are called **VACUUM TUBES**. A few types of tubes have a small amount of gas, such as neon, argon or a vapor of mercury, inside the envelope, and they are called gas-filled tubes. Because of the similarity of their actions, gas-filled rectifiers and vacuum tube rectifiers are frequently grouped as vacuum diodes.

In the field of electronics, the diode is the simplest form of an electron-controlling device. We have described the basic function of these devices and also mentioned the two most common types: the semiconductor diode and the vacuum diode. For many years, the only diode in common use was the vacuum diode, and its applications were many. Recently, however, the semiconductor diode has achieved widespread acceptance and continuing developments indicate that it will surpass the numerous applications of the vacuum diode, if indeed it has not done so already. At present, both types are in use with each having specific applications where it is better or where its advantages are required.

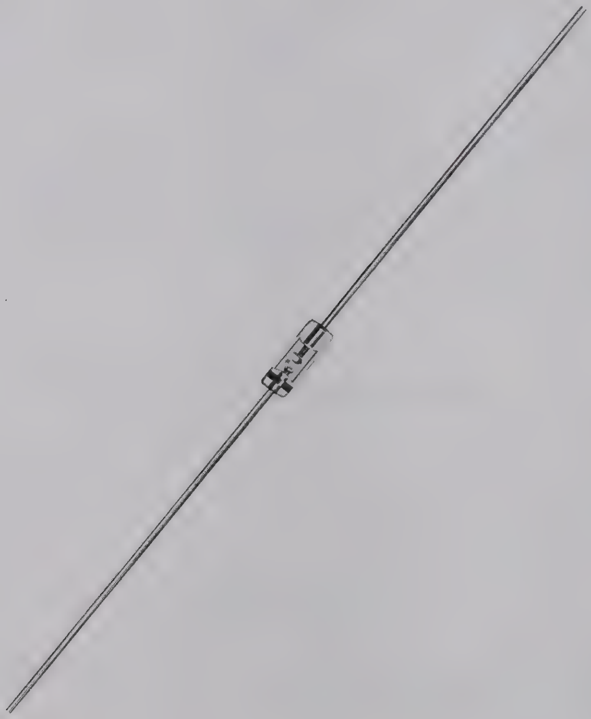
SEMICONDUCTORS

In order to understand semiconductors, as well as other related items, we must become familiar with the properties that they possess which make them behave as they do. Let's consider an atom of conductive material, which is composed of electrons orbiting around the nucleus. If an electron in outer orbit of an atom is not strongly attracted to the nucleus, it may move through the material as a free electron, if sufficient energy is applied. A major factor that determines the ease of movement is the form of the material or the way that the atoms group together in nature.

An atom seldom exists alone because it tends to combine with other atoms to form the various materials that we know. At room temperature, these materials may be either solids, liquids or gases. Semiconductors generally take the form of solids, so let's examine them more closely.

Some solid materials can give up electrons more easily than some other solid materials. This is because some of the electrons of the atoms of such materials are not as strongly bonded, or attracted, to the nuclei of their atoms. These materials are said to contain free electrons, because they easily give up electrons, or permit electron flow, when electric energy is applied to them. A conductor such as copper has more free electrons than does a semiconductor material such as silicon.

In some solid materials (such as semiconductors), the atoms form into definite groups called CRYSTALS. Within a crystal, the arrangement of the atoms is very orderly and takes the form of a LATTICE. Perhaps you have seen oranges or apples neatly piled in rows and layers in a grocery store. This is a lattice arrangement, and it shows how each individual item is linked to the others in the lattice to make up the whole group. In the crystal lattice of atoms, the linking between atoms is done by electrons and these, when sufficient energy is applied to the material, become the free electrons that flow from atom to atom. This movement of electrons provides the basis for conduction in the material.



This photo shows a typical low-power semiconductor diode. This type of diode generally has a glass or epoxy case.

Courtesy General Electric Co.,
Semiconductor Products Dept.

Several times we have mentioned energy as being a requirement for moving electrons from atom to atom in a material. An early lesson named some forms of energy: mechanical, electrical, heat, light, etc. Materials vary in their reactions to applied energy. If a material is subjected to a temperature of absolute zero (—459°F., or 459° below 0° Fahrenheit) and no other energy is present, there will theoretically be no electron movement. At any temperature higher than this extreme, some energy (in the form of heat) is being applied to material and some type of reaction will occur. Generally speaking, the higher the temperature, the greater the reaction. At room temperature, a conductor will have many free electrons, while an insulator will not. Semiconductors such as germanium and silicon rank between conductors and insulators in the number of free electrons that provide them with the property of conductivity.

Conduction

At room temperature, the free electrons of a semiconductor are considered to have relatively high energy levels. To produce a current (which is a flow of electrons), a voltage (V_S) must be applied across the semiconductor, as shown in Figure 1. Note the use of the letter V to designate the supply voltage in the semiconductor circuit. (It is common practice to use the letter V for voltage in semiconductor circuits and the letter E for voltage in electron tube circuits.) This electrical energy applied to the material provides enough additional energy to the electrons of the material so that more of them are freed. However, an unusual effect is noted that we should also be aware of.

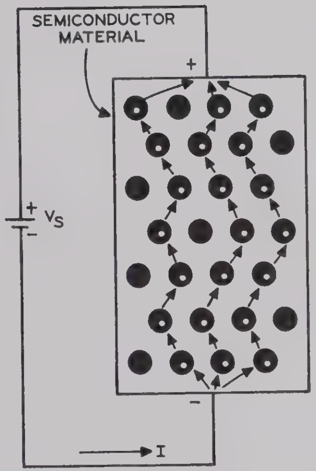


Figure 1

As an electron moves from one atom to the next, it leaves a vacancy in the outer orbit of the atom where the electrons circle the nucleus. This vacancy is called a **HOLE**. Every electron that is freed from an atom produces a hole. Since a hole is the absence of an electron, it can be thought of as having a positive charge equal to the negative charge of an electron. With this positive charge as an attractive force and the electrical energy from the applied voltage, an electron from a nearby atom may move, or "jump" to fill the hole. In turn, another electron may jump to fill the hole just created, but it likewise creates another hole in the atom it leaves.

In Figure 1, applied voltage V_S makes one end of the semiconductor material negative and the other end positive. In moving from atom to atom to fill holes, the jumping electrons move away from the negative end and toward the positive end of the material. In the sketch, the large black circles are atoms. Some of the atoms have holes, as shown by small white circles. The arrows show the directions in which electrons move. The electrons fill holes in the atoms to which they jump and form holes in the atoms that they leave.

We can think of this action as negative electrons moving in one direction or as positive holes moving in the other direction. In this way, a flow of holes is called a current, just as we call a flow of electrons a current. It may be handy to think of the holes as though they were particles, similar to electrons but with positive charges. Remember that the idea of a hole is for convenience only. Also, it is only in the case of crystals that the absence of an electron is called a hole.

Why do we think in terms of hole movement at all? Well, laboratory tests show that the holes move at about half the speed of free electrons at the same applied voltage. Due to this difference in speed, conduction by holes differs a little from that by free electrons.

The low-energy electrons that move by jumping from atom to atom are not free electrons. Their low energy prevents them from moving far enough away to become free of the atoms. They remain bound to the atoms, even while they are jumping from one to another. Thus, two kinds of electron flow are formed when a voltage is applied to a semiconductor. One flow consists of the high-energy free electrons, and the other consists of low-energy, atom-jumping electrons. These currents add to produce the total current, I, in Figure 1.

Since both hole conduction and electron conduction occur in semiconductors, the type of conduction being considered should be specified. From this point on, we shall use the term HOLE FLOW for conduction by the atom-jumping process. The term ELECTRON FLOW will be used for the flow of free electrons. This will avoid confusion between the two kinds of conduction.

An **INTRINSIC** semiconductor is one that does not contain atoms of other materials. In this type of pure crystal, whether or not a voltage is applied, whenever an electron leaves an atom as a free electron, it always creates a hole. As a result, the number of holes always equals the number of free electrons.

Two major factors that affect conduction in an intrinsic semiconductor have been mentioned: temperature and applied voltage. You will remember that there is no electron movement at absolute zero; there is also no hole flow conduction at this temperature.

At higher temperatures, small amounts of electron flow and hole flow take place when voltage is applied. At very high temperatures, many electrons leave their atoms and create an equally large number of holes. Then, the intrinsic semiconductor acts like a conductor.

However, it is not convenient to operate electronic equipment at extremes of temperature. The conductive ability of semiconductors at normal temperatures must be increased in another way. Certain impurities are added to the intrinsic semiconductor, so that it is no longer pure. It is now called a "doped" semiconductor. The result is an increase in one of the two kinds of conduction. As we will explain, either the holes or the free electrons increase, depending on the kind of impurity used.

N-Type Materials

An added impurity affects a semiconductor in either of two ways. If the impurity atoms have more electrons in their outer orbits than there are in the outer orbits of the semiconductor atoms, the excess electrons become free electrons. Then, with the impurity material added, the semiconductor has many more free electrons than it does holes. Because the impurity material has added free electrons to the semiconductor, the impurity is called a **DONOR**.

Arsenic, antimony and phosphorus are donor-type impurities. Because electrons have negative charges, a semiconductor with an excess of free electrons is called an **N-TYPE SEMICONDUCTOR**.

P-Type Materials

If there are fewer electrons in the outer orbits of the impurity atoms than in the outer orbits of the semiconductor atoms, the impurity atoms take elec-

Electronic power supplies like this use diodes to convert the ac line current into dc. In addition, special circuits maintain the output voltage constant under varying load conditions.

Courtesy Heath Company

trons away from some of the semiconductor atoms. Because it takes or "accepts" electrons, an impurity of this type is called an **ACCEPTOR**.

Aluminum, indium, boron and gallium are acceptor-type impurities. Due to the loss of electrons, the semiconductor atoms are left with more holes than free electrons. Since holes are considered to have positive charges, a semiconductor with an excess of holes is called a **P-TYPE SEMICONDUCTOR.**

Recombination

A voltage applied to either an N-type or a P-type semiconductor material causes current in the circuit. Within the semiconductor, the conduction is a flow of both free electrons and holes, as explained for the intrinsic semiconductor. However, in the doped semiconductor, the current is much greater for a given applied voltage at room temperature.

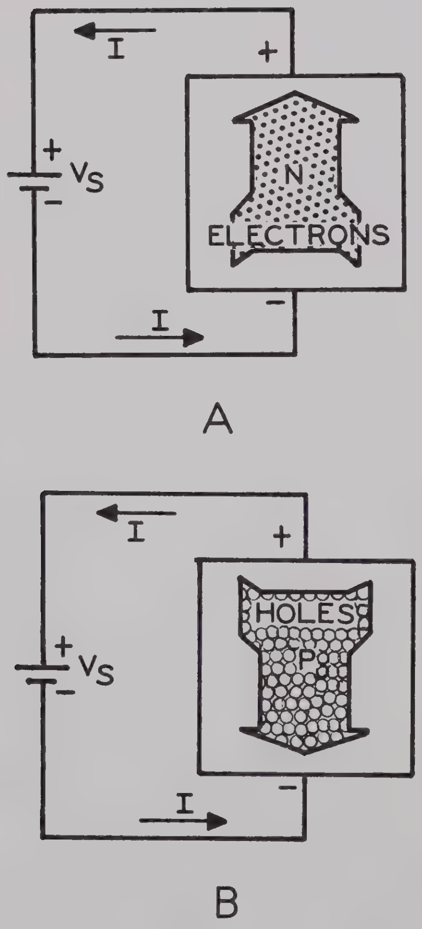


Figure 2

The greater conduction is provided by the type of excess current carriers the impurity has produced (holes or electrons). The excess current carriers are called the **MAJORITY CARRIERS**. *In N-type semiconductors, the majority carriers are free electrons, while in P-type semiconductors, the majority carriers are holes.*

Figure 2A shows a voltage, V_s, applied to a block of N-type semiconductor material. As shown by the arrows, current I leaves the negative terminal of the battery, passes through the semiconductor by the movement of the majority carrier electrons, and returns to the positive terminal of the battery. A large arrow shows the direction of the majority carriers in the semiconductor block. At the same time, holes, which are called **MINORITY CARRIERS** in this instance, move in the direction opposite to that of the free electrons.

When the holes reach the negative terminal of the semiconductor, they meet some of the electrons entering this terminal. When a hole and an electron meet, they combine with each other, and both cease to be current carriers. This action is called **RECOMBINATION**.

This would soon use up the supply of holes in the material. But new holes are formed in the semiconductor by electrons that leave their atoms and these electrons travel as free electrons to the positive terminal of the semiconductor.

The minority carriers add their effect to that of the majority carriers to produce the total current. However, the current due to the minority carriers is very small compared to that provided by the majority carriers.

Figure 2B shows a battery voltage, V_S, applied to a block of P-type semiconductor. As before, the external circuit current, I, consists of electrons that leave the negative terminal of the battery and return to the positive terminal. However, in the P-type semiconductor, the majority carriers are holes. In this example, many holes move through the semiconductor in the direction of the large arrow. The positive holes are repelled by the positive terminal of the semiconductor and attracted to the negative terminal.

Conduction by holes is not possible outside of the semiconductor material. When the holes reach the negative terminal, they combine with electrons entering the material at this terminal. This recombination action is the same as explained for the minority carriers in the N-type material of Figure 2A.

In the P-type material of Figure 2B, many holes are formed near the positive terminal by electrons leaving the material at this point. These holes replace the ones lost by recombination at the negative terminal. In this case, most of the semiconductor current is due to hole conduction. To this is added the minority current, consisting of the few free electrons that flow in the direction opposite that of the holes.

In both N-type and P-type semiconductors, the total current is the sum of the flows of free electrons and holes. However, the conduction is mostly the movement of free electrons in the N-type materials, and mostly the movement of holes in the P-type materials.

In any semiconductor material, holes and free electrons are lost due to recombination within the material. This occurs regardless of whether or not a voltage is applied across the material. But in every instance, new free electrons and holes are formed as the result of electrons gaining enough energy to leave their atoms. A balance is reached when the recombination rate equals the rate at which the new electron-hole pairs are being formed.

THE SEMICONDUCTOR JUNCTION DIODE

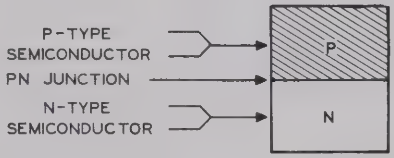


Figure 3

To form a semiconductor diode, a P-type semiconductor and an N-type semiconductor are combined. The junction between the P-type and N-type materials is called a **PN JUNCTION**. This diode unit is represented in Figure 3. **JUNCTION DIODES** are constructed in many ways, but in every

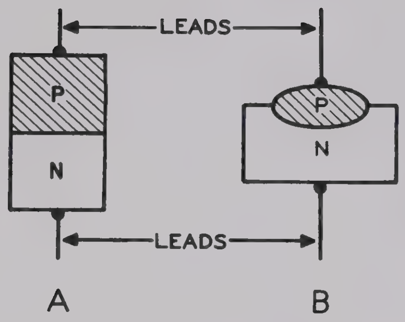


Figure 4

diode the two semiconductor materials are joined to form a single piece. There are two types of semiconductor junction diodes. One is called a GROWN JUNCTION, as shown in Figure 4A. In the grown junction diode, the PN junction is formed by adding the proper impurities to the semiconductor material as it is "grown" or manufactured. The second type is called a DIFFUSED JUNCTION, shown in Figure 4B. In the diffused junction diode, an impurity gas is allowed to diffuse into the semiconductor material to form the PN junction.

Combining N-type and P-type semiconductors to form a semiconductor diode seems likely to affect the majority carriers in each material, doesn't it? Let's see what happens.

Remember that every free electron in the N-type material became free by escaping from an atom, leaving the atom with a positive charge. For every wandering free electron, there is a positively charged atom at some point in the N-type material. The total of positive atoms is equal to the total of free electrons. Therefore, the material as a whole is electrically neutral.

Also, for every hole in the P-type material, there is an atom with a negative charge at some point in the material. For this reason, the P-type material is electrically neutral also. If a piece of N-type semiconductor is merely placed in contact with a piece of P-type semiconductor, there is no difference of potential between them.

When N-type and P-type semiconductors are joined to form a PN junction, it is not the same as just simply placing them together. They are bound very closely to form a single piece. This joining permits the majority carriers near the PN junction to be attracted to each other. They move closer together, combine, and therefore cancel out. Due to this cancelling action at the junction, the N-type material loses some of its electrons and the P-type material loses some of its holes. *This action takes place only near the junction.*

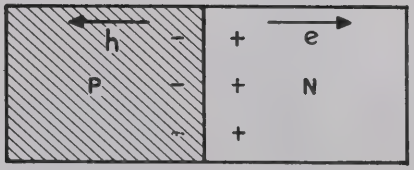


Figure 5

As a result, the N-type material is left with a positive charge near the junction, and the P-type material is left with a negative charge near the junction, as shown in Figure 5. This means that a small difference of potential is produced across the junction. This potential difference is called POTENTIAL BARRIER or HILL.

The positive charge of the N-type material repels the holes of the P-type material away from the junction, as shown by the **h** (hole) arrow in Figure 5. Likewise, the negative charge of the P-type material repels the electrons

The following Practice Exercise questions cover the subjects which you have just studied. They are:

RECTIFIERS

SEMICONDUCTORS

CONDUCTION

N-TYPE MATERIALS

P-TYPE MATERIALS

RECOMBINATION

1. An electron device consisting of two electrodes is called a (a) vacuum tube, (b) semiconductor, (c) diode, (d) electrode.

2. A voltage that changes polarity periodically is called ______________________________.

3. Changing ac to dc is called ______________________________.

4. An insulator is a material that, at room temperature, (a) has few free electrons, (b) has many free electrons, (c) is crystalline in structure, (d) has a lattice structure.

5. A semiconductor is a substance that has less free electrons than a conductor but more than an insulator. True or False?

6. Electron flow can be defined as a flow of __________ electrons.

7. When an electron is freed from a crystal atom, it leaves a ____________.

8. The holes in a semiconductor material are considered to be (a) negative, (b) neutral, (c) crystals, (d) positive.

9. In a semiconductor, it is possible to have current flow of both free electrons and holes. True or False?

10. Holes and free electrons move at the same speed. True or False?

11. What is an intrinsic semiconductor?

12. A doped semiconductor is one which (a) is defective, (b) conducts only at high temperatures, (c) has added impurities.

13. A semiconductor with an excess of free electrons is called (a) N-type, (b) P-type.

14. In an N-type semiconductor, the excess electrons are the majority carriers and the holes are the minority carriers. True or False?

15. Conduction by holes is possible in the external connecting leads of a semiconductor. True or False?

16. Conduction is mostly the movement of ____________________ ________ in the N-type materials, and mostly the movement of ________ ________ in the P-type materials.

17. What is meant by recombination within a semiconductor material?

of the N-type material away from the junction, as shown by the **e** (electron) arrow. In this way, the region near the junction forms a "barrier" that prevents additional recombination of majority current carriers.

To produce current in the diode, the free electrons and holes must gain enough energy to overcome the "hill" and cross over the junction. The most common source of this energy is an electric power source such as a battery. In Figure 6, battery voltage V_S is applied across the terminals of a PN junction. The positive terminal of the battery connects to the P-type semiconductor, and the negative terminal connects to the N-type. Both the holes in the P-type material and the electrons in the N-type material are repelled toward the junction by the battery voltage. This is indicated by the **h** and **e** arrows at the right of the diode.

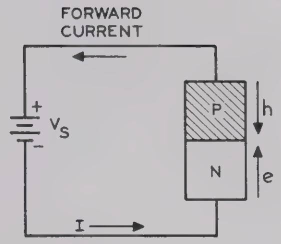


Figure 6

Near the junction, the holes and electrons combine with each other. They no longer are moving current carriers. Before combining, some of the holes travel a short distance into the N-type material, and some electrons travel a short distance into the P-type material.

At the other end of the N-type material, electrons arrive from the negative terminal of the battery to replace those that combined with holes at the junction. Similarly, at the other end of the P-type material, electrons leave the diode to flow to the positive terminal of the battery. This forms new holes to replace those cancelled at the junction.

Therefore, with the battery voltage applied to the diode, as shown in Figure 6, electrons from the battery enter the N-type material, and electrons leave the P-type material to flow to the battery. Within the diode, electrons and new holes move toward the junction. There, they cancel each other by combining. This action provides conduction by majority carriers in the diode. The electron flow in the external circuit is current in the direction indicated by arrow I.

Current is produced in the circuit of Figure 6 because the applied battery voltage overcomes the potential hill at the diode's junction by decreasing the junction's resistance to current. When the battery is connected in this way, with its positive terminal to the P-type material and its negative terminal to the N-type material, the PN junction is said to be **FORWARD BIASED**. The current in the semiconductor diode, composed of electron flow in the N-region and hole flow in the P-region, is called **FORWARD CURRENT**.

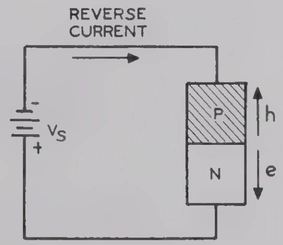
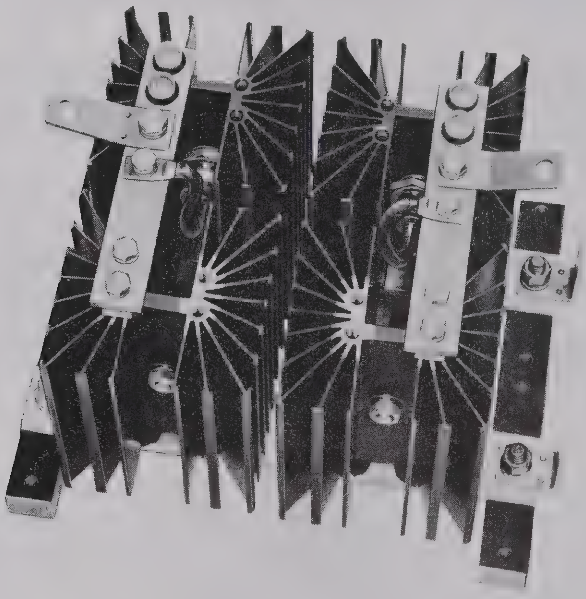


Figure 7

If the battery is connected to the diode as in Figure 7, with the negative battery terminal toward the P-type material and the positive terminal toward the N-type, the junction is said to be **REVERSE BIASED**. With this arrangement, the holes in the P-type material move away from the junction due to the attraction of the negative battery voltage. Likewise, the electrons in the N-type material move away from the junction, due to the attraction of the positive battery voltage. These movements are shown by the **h** and **e** arrows at the right of the diode in Figure 7.

As a result, almost no majority carriers are left near the junction. The reverse bias increases the potential hill near the junction. This increases the junction resistance, and there is almost no conduction by majority carriers across this region.



To increase the current-carrying capability of these semiconductor diodes, they are mounted on finned heat sinks. The heat sinks provide increased surface area to help dissipate the heat.

Courtesy General Electric Co.,
Semiconductor Products Dept.

However, the reverse bias does cause a very small current due to conduction by minority carriers. As explained earlier, these carriers are electrons in the P-region and holes in the N-region. Due to the battery voltage, the minority carrier electrons in the P-type material move toward the junction. There, they combine with minority carrier holes also moving through the N-type material toward the junction. For each electron-hole combination, an electron from the battery negative terminal enters the P-type material and an electron leaves the N-type material to flow to the positive terminal of the battery.

Because it is caused by reverse bias, the current due to minority carrier conduction is called **REVERSE CURRENT**. In the external circuit, the reverse current is electron flow away from the N-type material and toward the P-type material. As always, electrons leave the battery at the negative terminal and enter it at the positive terminal. This holds true whether the semiconductor diode is conducting forward or reverse current.

There is no arrow labeled I in Figure 7 because the small reverse current may be ignored so far as the rectifier action of the semiconductor diode is concerned. In examining diode circuit action, only forward current will be considered. The reverse current has been mentioned at this time because it does exist, however small, in the semiconductor type diode, and because it forms one of the important actions in transistors. In addition, there is one class of semiconductor diodes, called **ZENER DIODES**, that are designed to operate with reverse current.

The schematic symbol for a semiconductor diode is shown in Figure 8. At the right of the symbol, arrow I_F shows the direction of forward electron flow through the diode. The rectangle at the bottom of the symbol represents the **CATHODE**. This is the negative electrode of the diode. The triangle at the top of the symbol is called the **ANODE**. This is the positive electrode of the diode.

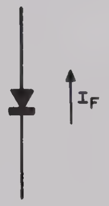


Figure 8

The voltage-current relationships of the semiconductor diode are shown by the curve of Figure 9. Distance along the horizontal axis represents changes of voltage. Distances along the vertical axis are changes of current. Voltages to the right of point O are forward bias voltages. Those to the left of this point are reverse bias voltages. At point O, the bias is zero. The bias goes up as we move either to the left or right of point O. Increases in distance above the horizontal base line indicate increases in forward current, and increases in distance below the base line indicate increases in reverse current.

The steep upward slope of the curve in the region from point O to point A shows that the forward current increases rapidly with increases in forward bias. However, in the region from point O to point B, the reverse bias can be increased to a high value with very little increase in reverse current. At point B, the diode resistance is suddenly overcome. In the region from point B to point C, a small increase of reverse bias causes a rapid increase of reverse current. The voltage at point B is called the ZENER VOLTAGE, or sometimes, the breakdown voltage.

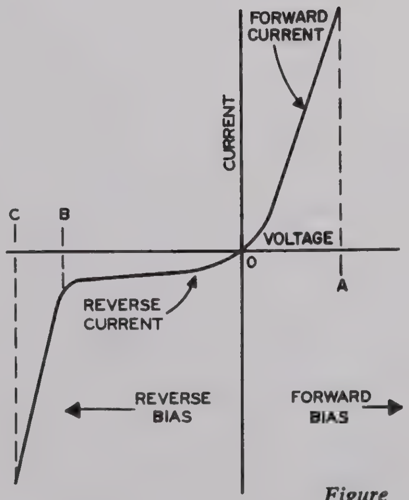


Figure 9

Except for the zener diode, which is designed to operate in the reverse bias region, semiconductor diodes are generally used in forward bias applications where they conduct forward current. This type of operation means that the maximum value of reverse bias applied must be less than the zener voltage. This maximum reverse bias voltage is also called **PEAK INVERSE VOLTAGE**, and it is a very important factor concerning diodes. It is usually specified by the diode manufacturer so that the safe limits of operation are known because, unless a diode is designed to operate in the zener voltage region, it may be destroyed by the large value of reverse current.

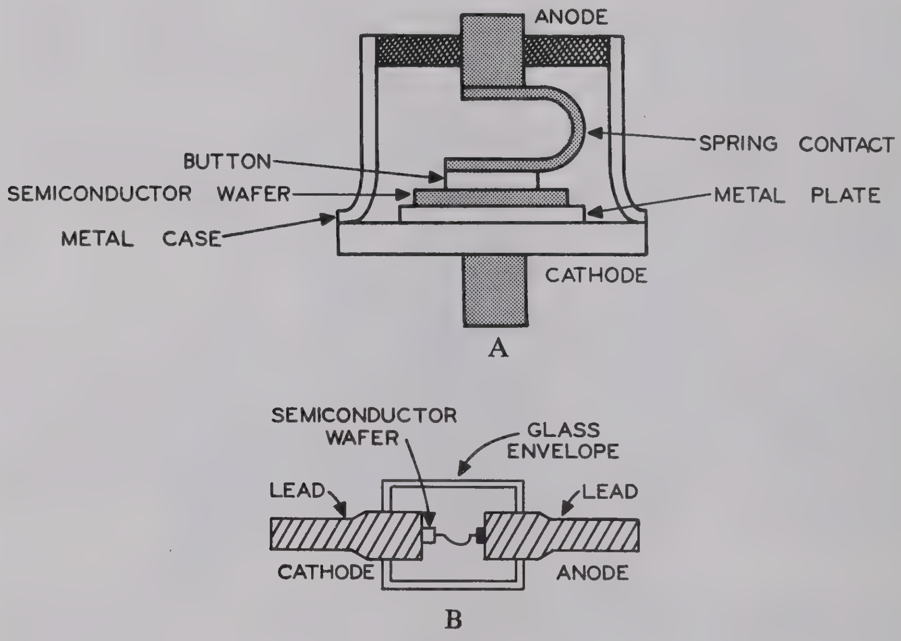


Figure 10

Figure 10A shows a greatly enlarged view of the construction of one type of PN junction diode. The metal plate and button make electrical connections to the cathode and anode of the semiconductor wafer containing the PN junction. Figure 10B shows an enlarged view of another construction arrangement. Here, the semiconductor wafer is bonded to one of the leads and a wire makes contact to the other side of the wafer. The envelope may be made of glass or the entire diode can be encapsulated in a plastic or epoxy material.

POINT CONTACT DIODES

Another type of semiconductor diode is the POINT CONTACT DIODE. This type of semiconductor diode is different from the PN junction diode, because it does not have the normal PN junction. Figure 11 shows the basic construction of a point contact diode. The sharp point of a tungsten wire rests against a slab of N-type material. The tungsten point or "catswhisker," as it is called, is the anode, while the slab of N-type material is the cathode. The diode is forward biased when the point is made positive with respect to the N-type base material. The positive potential applied to the point pulls free electrons away from the point. The holes that are generated migrate into the N-type material where they recombine with the excess electrons. The overall result is a forward current, I_F, flowing through the diode and external circuit, as shown in Figure 11. Like any semiconductor device, both holes and electrons constitute the current within the semiconductor material, while the current in the external circuit consists of electrons.

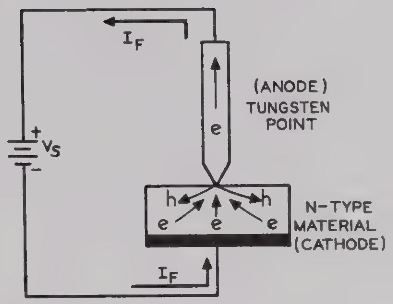


Figure 11

Figure 12 shows the reverse bias conditions for a point contact diode. The negative potential on the point attempts to push free electrons toward the N-type material. However, the N-type material has an excess of electrons and tends to repel them. A small number of electrons in the N-type material are attracted to the positive potential, causing a small reverse current. If a high enough reverse bias voltage is applied, the electric field will generate the hole-electron pairs, causing breakdown within the diode and a high reverse current.

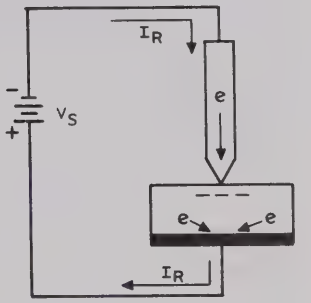


Figure 12

Since forward current is produced when holes are injected into the N-type material, the conduction action of the point contact diode is referred to as **HOLE INJECTION.**

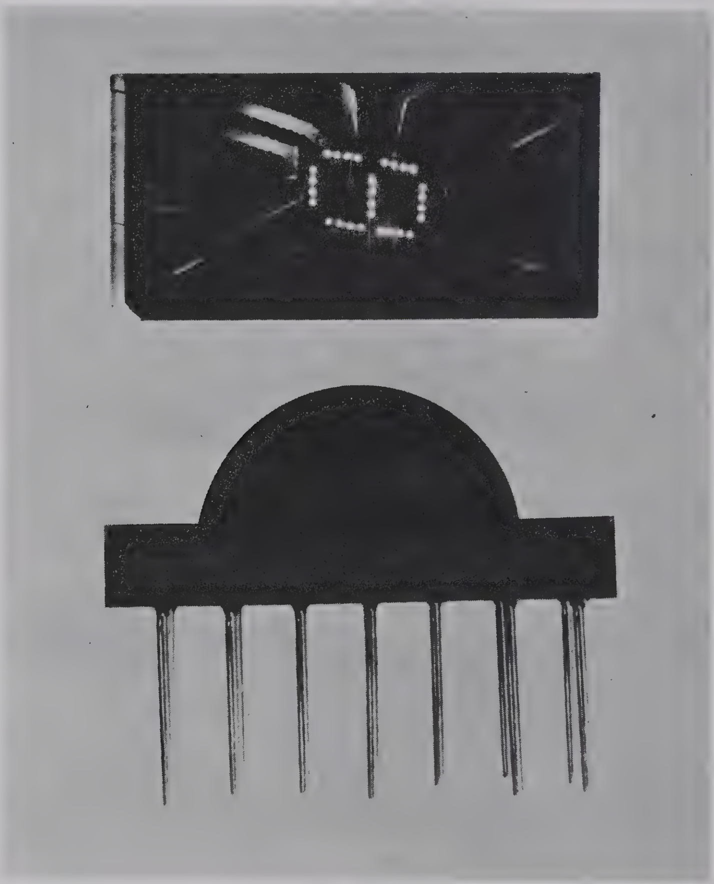
LIGHT EMITTING DIODES

We know that the free electrons in a semiconductor material are relatively high energy particles; this energy is a requirement for them, not only to break free from the atom in the first place, but to continue their movement from atom to atom in the material. We also know that this energy may come from various sources and in different forms; our earlier discussion mentioned using heat and electrical energy to free the electrons.

At the PN junction in semiconductor materials, the process of recombination, which was mentioned earlier as the combining of an electron and a hole, produces an excess of energy because the energy requirement of the electron drops when it combines with the hole. In some special semiconductor materials, this excess energy is given off in the form of light (another type of energy) at the PN junction. These special semiconductor diodes have the property of emitting light, and this is the reason for their name, LIGHT EMITTING DIODE, which is abbreviated LED.

Because the area of the PN junction is small, the amount of light emitted is also small. LED's are usually packaged with a magnifying lens on top of the light emitting surface to optically increase the size of the visible light emitter. The shape of the light emitting surface (the PN junction) is usually a very small square or rectangle. Several of these LED's may be combined in one larger unit to provide a horizontal and vertical pattern of dots or short lines. These may then be turned on individually, each forming a part of a letter or number in a display device that shows numbers or letters as its indication.

A reddish light is the color most frequently seen in LED displays. This color occurs because of certain qualities of the special semiconductor materials used, which are combinations of the chemical elements, gallium, arsenic and phosphorus. A recent development is a group of compounds of only gallium and phosphorus, which provide, depending on the amount of each element used, green, yellow or red emitted light.



Light emitting diodes form the pattern of this seven-segment numeric display unit. Numbers from 0 to 9 may be displayed by activating various combinations of segments. The magnifying lens is visible in the side view, as are the circuit connection leads.

Courtesy Litronix

SELENIUM RECTIFIERS

Another type of diode or rectifier is the SELENIUM RECTIFIER. This unit was widely used before PN junction diode was developed. Although still in use today, many of its applications have been taken over by PN junction diodes.

Figure 13 shows the construction of a selenium rectifier. Selenium in crystal form is deposited upon an aluminum plate. A counter electrode is then deposited over the selenium. The blocking layer is formed by applying a high reverse voltage to the cell for a period of time. The blocking layer has the property of passing electrons in one direction and not in another. That is, the blocking layer will allow electrons to flow from cathode to anode but offers resistance to electron flow from anode to cathode.

Several other types of material can be used to form a METALLIC RECTIFIER CELL, like the selenium unit of Figure 13. Copper oxide is one material that has been used.

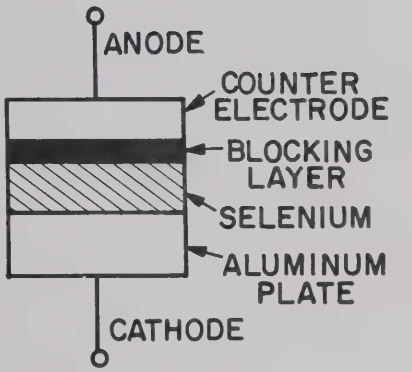


Figure 13

VACUUM TUBES

In 1883, while working on the electric lamp, Thomas Edison mounted a metal **PLATE** inside the glass envelope of a lamp and connected it to the battery used to light the lamp filament. He then connected an ammeter as shown in Figure 14. With the plate connected through the meter to the positive terminal of the battery, the meter pointer moved. This proved there was a current through the lamp between the filament and plate. With the plate connected through the meter to the negative terminal of the battery, the meter pointer did not move, which meant that there was no current through the lamp between the filament and plate. This action became known as the "Edison Effect."

Because this Edison Effect occurred within the vacuum of the experimental lamp, it is considered the basis for the vacuum tube. The lamp of Figure 14 contains two electrodes, the filament and the plate. Edison noted, but could not definitely explain, that the current flowed in one direction only, by some invisible path between the filament and the plate. At that time, the heating of the filament (by passing an electric current through it) was only intended to cause it to radiate light. We know now that the Edison Effect is the emission of electrons from the heated filament.

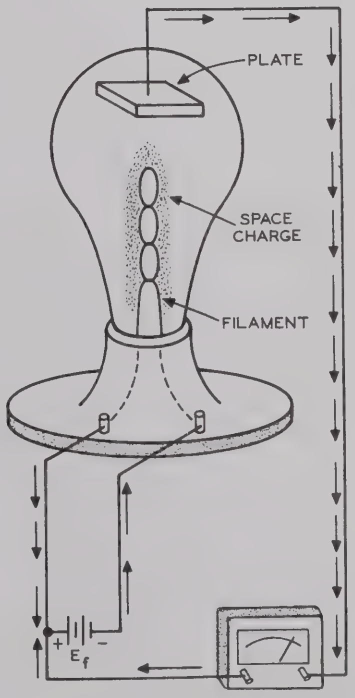


Figure 14

Emission

The solid, metallic wire of a lamp filament is made up of molecules. Within the molecules are atoms. Each atom has a number of electrons orbiting around its nucleus. The more energy an electron has, the farther it is from the nucleus. The escape of electrons from a substance is very much like the escape of water particles in the form of steam from a pan of boiling water.

Today, the reason for the meter pointer deflection in Figure 14, as observed by Edison, is clear. Voltage E_f in Figure 14 causes a current in the filament. Electrons flow from the negative terminal of the battery, as shown by the arrows. The current in the filament causes it to become hot and some of the electrons in the heated filament gain enough energy to break loose from the metal surface and escape into the space around the filament. This **ELECTRON EMISSION** from a heated metal **ELEMENT** is known as **THERMIONIC EMISSION.** This is the action that occurs within our present-day vacuum tubes.

If the plate is connected to the positive terminal of the battery, electrons flow to the plate. From the plate they flow through the meter to the positive terminal of the battery, through the battery, and from the negative terminal of the battery to the filament—making a complete electron circuit. This electron flow causes movement of the meter pointer.

Edison also noticed that, when the plate was connected to the negative terminal of the battery, the meter pointer did not move, which meant that there was no electron flow. This can be understood if we recall one of the basic laws of electricity and electronics—unlike electric charges attract and like electric charges repel. Since the electrons have negative charges, they do not flow to the negative terminal of the battery. Let's consider these factors, in addition to some new ones, from the viewpoint of their action in a vacuum tube, rather than in an experimental lamp.

The Space Charge

The negative electrons that escape into the region around the filament are known as the **SPACE CHARGE.** You might think that the space charge would keep building up as more electrons escape from the heated filament. But shortly after the filament heats up, the cloud of negative electrons causes the space charge to become more negative than the filament. As a result, the space charge repels the negative electrons back into the filament.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE SEMICONDUCTOR JUNCTION DIODE

POINT CONTACT DIODES

LIGHT EMITTING DIODES

SELENIUM RECTIFIERS

18. What is formed when a P-type and an N-type semiconductor are combined into a single structure?

19. In a PN junction, the N-type material loses electrons to the P-type material and the P-type material loses holes to the N-type material. True or False?

20. The small potential produced across a PN junction due to the cancelling effect of combining holes and electrons is called (a) a donor, (b) the applied voltage, (c) a potential hill.

21. To produce current in a semiconductor diode, the free electrons and holes must gain enough energy to overcome the potential hill. This energy is usually provided by (a) a power supply, (b) impurity atoms, (c) majority carriers, (d) recombination.

22. A PN junction is forward biased when the positive terminal of a battery is connected to the ________-type material and the negative terminal is connected to the ________-type material.

23. Current due to minority carrier conduction is called forward current. True or False?

24. Draw the schematic symbol for a semiconductor diode in the space provided. Show an arrow to indicate the direction of forward current through the diode. Label the cathode and the anode.

25. A point contact diode employs (a) two PN junctions, (b) a junction formed by a wire pressing on a piece of semiconductor material.

26. Current flow in a point contact diode is the result of (a) electron injection, (b) hole injection.

27. Light emitting diodes produce light from energy released during recombination. True or False?

28. Most LED's emit a ________ light.

29. What area in the selenium rectifier permits electron flow in only one direction?

For a given filament temperature, there is a balance when the number of electrons repelled back to the filament equals the number that escape due to heat. Just how much of a space charge there is depends on the temperature and the type of material used as the filament.

Tube Operation

In a vacuum tube, to simply connect the plate to the positive side of the filament seldom provides proper operation. Instead, separate voltage sources are used to heat the filament and to provide voltage for the plate of the tube. In Figure 15, battery E_f heats the filament and battery E_{bb} provides the plate voltage. The filaments in these diagrams are shown by two lines which come together at a point inside the tube, like a sideways V.

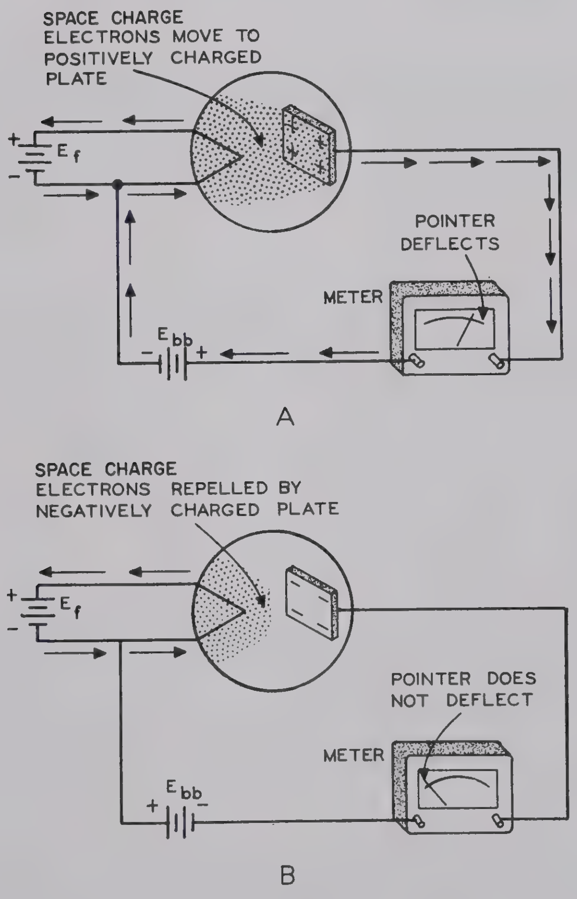


Figure 15

In Figure 15A, the heated filament emits electrons to build up a space charge. Battery voltage E_{bb} makes the plate positive with respect to the filament. Therefore, electrons are attracted from the space charge to the plate. The meter pointer moves because the electron flow is complete from the plate through the battery, from the negative terminal of the battery to the filament and space charge, and from the space charge to the plate.

In Figure 15B, a space charge again is built up by electrons leaving the filament. But here, the plate connects through the meter to the negative terminal of battery E_{bb}. This places a negative potential on the plate, and the negative electrons in the space charge are repelled by the negative plate. Since electrons do not flow between the space charge and the plate, there is no current to deflect the pointer of the meter.

Let's review the action of Figure 15. When the plate is positive with respect to the heated filament, there is an electron flow between them; but when the plate is negative, there is no electron flow.

Figure 15 shows the DIRECTLY HEATED EMITTER, in which the electrons are emitted by the heated **FILAMENT**. Another type of emitter is commonly used as an electron source in vacuum tubes; it is called the INDIRECTLY HEATED EMITTER, and it is shown in Figure 16.

In this arrangement, the filament is not the source of electrons although it still is heated by the filament power source. Instead, a piece of metal called a CATHODE is placed between the plate and the filament. The filament heat raises the temperature of the cathode until it emits electrons.

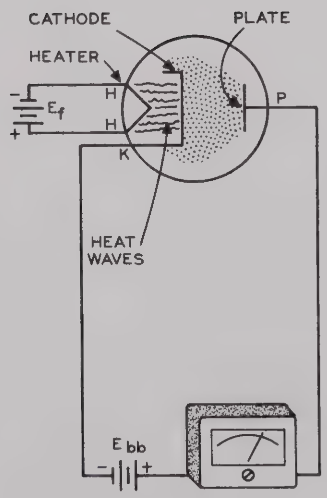


Figure 16

In the future, when we refer to the wire that heats the cathode in an indirectly heated emitter, we will call this a **HEATER**. When we refer to a directly heated emitter, we will call it a filament.

Notice that there are two separate electric circuits in Figure 16. The circuit composed of the E_f battery, the heater and the connecting wires is called the HEATER CIRCUIT. The E_{bb} battery, cathode, meter, plate and connecting wires form the PLATE CIRCUIT. (In Figure 15, the term FILAMENT CIRCUIT would be substituted for HEATER CIRCUIT.)

The electric action in Figure 16 is the same as in Figure 15A. When the plate is positive with respect to the cathode, electrons are attracted from the space charge to the plate. They pass through the meter to the positive terminal of the battery, through the battery to the negative terminal, and back to the cathode. The emission of electrons tends to give the cathode a positive charge. To replace electrons attracted by the plate and to stop the cathode from building up this positive charge, the negative terminal of the E_{bb} battery supplies electrons to the cathode.

Electrode Construction

Figure 17 shows three types of directly heated emitters, which differ in the methods of support. In each type, the supports connected to the ends of the filament are conductive. They complete an electric circuit from the filament to an external voltage source through the base of the tube.

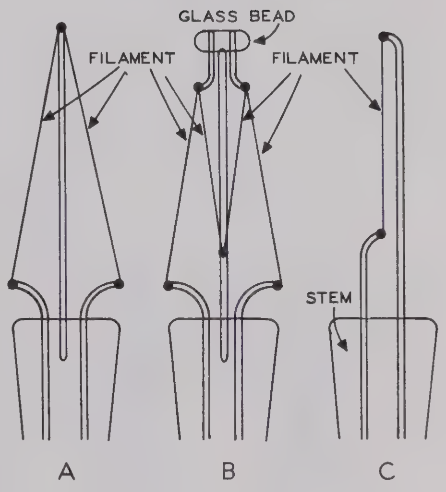


Figure 17

Some directly heated emitters are made of pure tungsten. This metal does not vaporize when heated to emitting temperature. However, tungsten needs a rather large current to achieve the desired temperature.

A more common directly heated emitter is the thoriated filament. This is made by putting a small amount of thorium oxide and carbon into a tungsten wire. When heated, the thorium works its way to the surface of the filament where it forms a thin layer. Emission takes place from this layer at temperatures much lower than those needed for emission from pure tungsten. As the thorium on the surface is used up, a new supply "boils out" from inside the wire. This renews the outer layer.

Another common emitter is the oxide-coated type. It consists of a platinum or nickel wire coated with an oxide of barium, strontium or calcium. These materials readily emit electrons when heated. This type of emitter is widely used in small tubes because it operates at temperatures only slightly more than half those required for the thoriated-filament type.

Within certain limits, electron emission varies with the temperature, and temperature varies with the filament current or voltage. In this lesson, we have described the use of batteries as filament voltage sources. However, the most common voltage source is alternating current. Not only is this cheaper, but also by means of transformers, the common 110-120 volt, 60-Hz ac supply voltage can be changed to any desired filament voltage.

Alternating current drops to zero each time it reverses direction. Using a 60-Hz ac supply to heat the filament of an electron tube causes changes of temperature and some variation of emission. A radio, for example, would have too much hum if the emitter temperature varied at a 60-Hz rate. Because of this hum problem, indirectly heated tubes are preferred when the heater voltage is ac.

Let's compare this to making steam. Put a small amount of water into a thin-walled pan on a stove and bring the water to a boil. Now raise and lower the heat under the pan. There will be a lot of steam when the heat is high, and very little steam when the heat is low. Next, put the same amount of water into a thick iron pan and repeat the test. The pan holds the heat for a long time, and the changes of heat must be very slow before the amount of steam is affected.

In a heater-cathode arrangement, the heater temperature follows the changes of heater voltage because the heater wire is very thin. The cathode, being heavier, does not vary its temperature at a 60-Hz rate.

Like the directly heated types, the cathode type of emitter is made of metal, coated with an oxide. It is made in the form of a cylinder that fits snugly around the heater. The heater itself is a tungsten or tungsten-alloy wire coated with an insulating material.

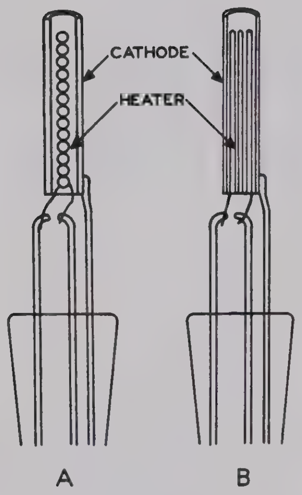


Figure 18

Two types of indirectly heated emitters are shown in the cutaway views of Figure 18. In Figure 18A, the heater is wound in a double spiral; that is, the wires are twisted about each other. Figure 18B shows a folded heater. Different tube manufacturers hold patents for (or favor) one of these two methods. Usually, there are separate conducting supports for the heaters and cathode. These pass through the base of the tube to connecting pins.

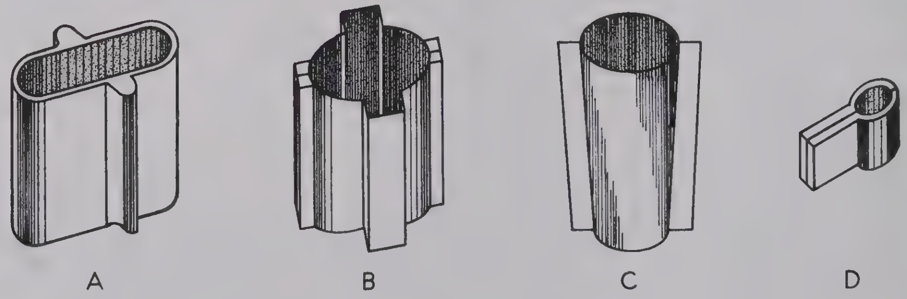


Figure 19

The purpose of the plate of a tube is to collect the emitted electrons. Usually, the plate is shaped like one of those shown in Figure 19, mounted so that it surrounds the emitter. Virtually all electrons emitted from the cathode are attracted directly to the plate. Nickel, iron, molybdenum, tantalum or alloys of these metals are used for plate material. They produce a strong plate which easily dissipates heat.

Electron tubes are constructed in a wide variety of sizes and shapes to suit various requirements. In this photo, the third tube from the left in the back row is a high-voltage rectifier of the type commonly used in television receivers.

Courtesy General Electric Co.,
Tube Department

Symbols and Abbreviations

In some diagrams for electron tube circuits, the leads entering a tube envelope are marked by letters. These letters stand for the name of the part to which the lead connects. In Figure 16, P stands for plate, H stands for heater, and K is used for the cathode. (Although the word "cathode" begins with the letter C, this letter is not used because it is the standard letter symbol for another circuit component.) A filament in a tube symbol is usually labeled F.

Figure 16 shows the schematic symbol of an indirectly heated diode tube. The circle represents the envelope, and the various parts are as shown. (In the directly heated tube, the cathode is omitted since the filament is the emitter.) Parts of a tube such as the filament or cathode and the plate are called ELEMENTS. A heater is not considered to be an element because it only provides heat and is not part of the active tube circuit. A diode tube is one with two elements: (1) filament or cathode and (2) plate.

THE VACUUM TUBE DIODE

A cutaway view of a typical diode tube is shown in Figure 20A. Connections are made to the tube elements by metal pins that extend through the bottom or base. When assembled with the envelope in place, a tube of this type looks like Figure 20B. The envelope usually carries a marking (combination of numbers and letters) to identify the tube. Tube envelopes like that of Figure 20B are about 3/4 inch in diameter and are classed as MINIATURE types.

A base pin arrangement is pictured in the bottom view of Figure 20C. Notice that the pins are numbered from 1 to 7 in the CLOCKWISE direction, starting with the pin after the wide gap. Since the tube socket has a matching alignment of holes, the gap makes it almost impossible to place the tube into its socket in the wrong position.

Miniature 9-pin tubes that are slightly larger but otherwise resemble the 7-pin tubes are also available. Some very tiny tubes have been developed for equipment where space was limited. Instead of pins, wires are brought out from the tube base and soldered directly into the circuit. These tubes are called SUBMINIATURE tubes.

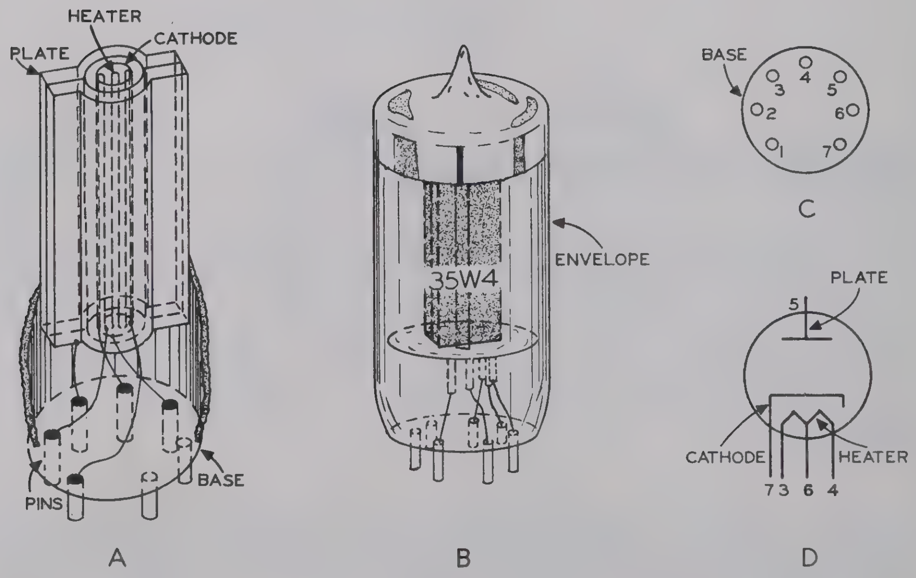


Figure 20

The following Practice Exercise questions cover the subjects which you have just studied. They are:

VACUUM TUBES

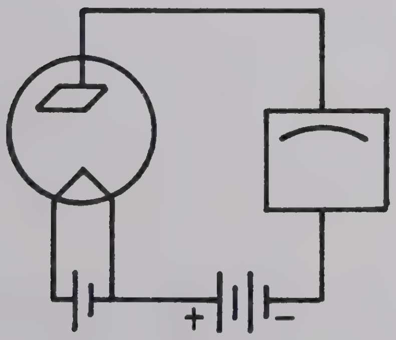
- **EMISSION**
- **THE SPACE CHARGE**
- **TUBE OPERATION**
- **ELECTRODE CONSTRUCTION**
- **SYMBOLS AND ABBREVIATIONS**

30. Electron emission from a heated metal element is known as (a) space charge, (b) Edison Effect, (c) thermionic emission.

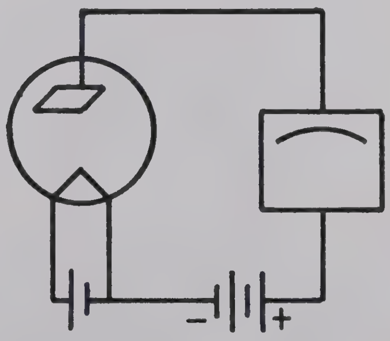
31. When Thomas Edison made a connection from the plate in his lamp to the ____________________ terminal of a battery, the meter indicated a current flow.

32. A cloud of electrons builds up around a heated filament as electrons escape from the filament. This cloud of electrons is known as the ________________________.

33. In the circuits below, draw pointers on the meters to show current flow or lack of current flow. Also show the space charge.



A



B

34. A filament is the ______________ heated emitter of a vacuum tube.

35. A cathode is the ______________ heated emitter of a vacuum tube.

36. The device that heats the cathode is called a ______________.

37. With an indirectly heated emitter, the electrons are emitted from the heater. True or False?

38. The tube element which attracted the emitted electrons is the ______________.

39. Draw the schematic symbols of: (a) a directly heated diode tube, and (b) an indirectly heated diode tube. Label the parts of each diode.

40. A thoriated tungsten filament acts as an emitter when (a) its temperature exceeds the pure tungsten wire emission temperature, (b) the temperature (lower than for pure tungsten wire) causes thorium to reach the filament surface, (c) it is connected with a positive polarity with respect to the plate.

41. Thermionic emission from a cathode (a) is relatively steady, (b) varies greatly.

In some schematic diagrams, a number is added near each part of the tube symbol to show which base pin connects to which part inside the tube. As shown in Figure 20D, the inverted "W" heater symbol differs slightly from the "V" heater symbol of Figure 16. With this type of heater, there are three pin connections.

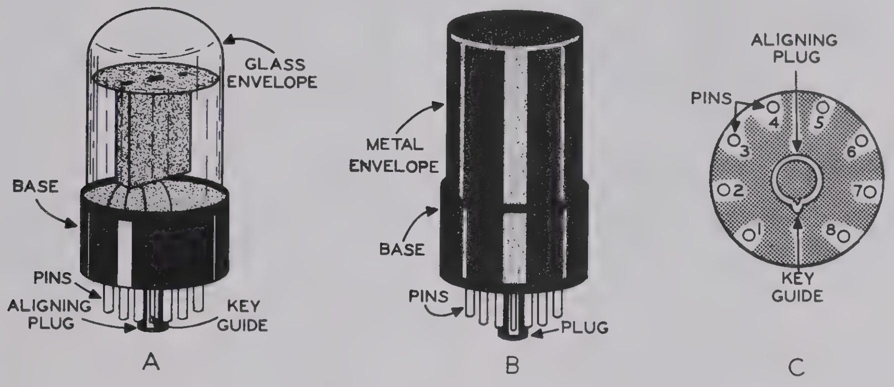


Figure 21

Some tubes, larger than the miniature types, may be manufactured with either glass or metal envelopes. Examples are shown in Figure 21A and 21B. These tubes are called OCTALS. They have eight pins and an ALIGNING PLUG with a KEY that extends from the base of the tube to help guide the tube into its socket. These tubes have a base diameter of slightly more than 1 inch.

Viewed from the base, as in Figure 21C, the octal tube pins are numbered from 1 through 8 in a CLOCKWISE direction from the key. The pins are spaced evenly around the base of the tube, but the key fits into a corresponding opening in a socket so that the tube may be inserted in only one position. Many octal tubes do not have pins in all eight positions, but the spacing of the remaining pins is as shown in Figure 21C.

Figure 22 shows the important measurements in a vacuum tube diode circuit. E_b represents a meter that measures the average **PLATE VOLTAGE**, and I_b represents a meter that measures the average **PLATE CURRENT**. Notice that plate voltage E_b is measured from plate to cathode and that plate

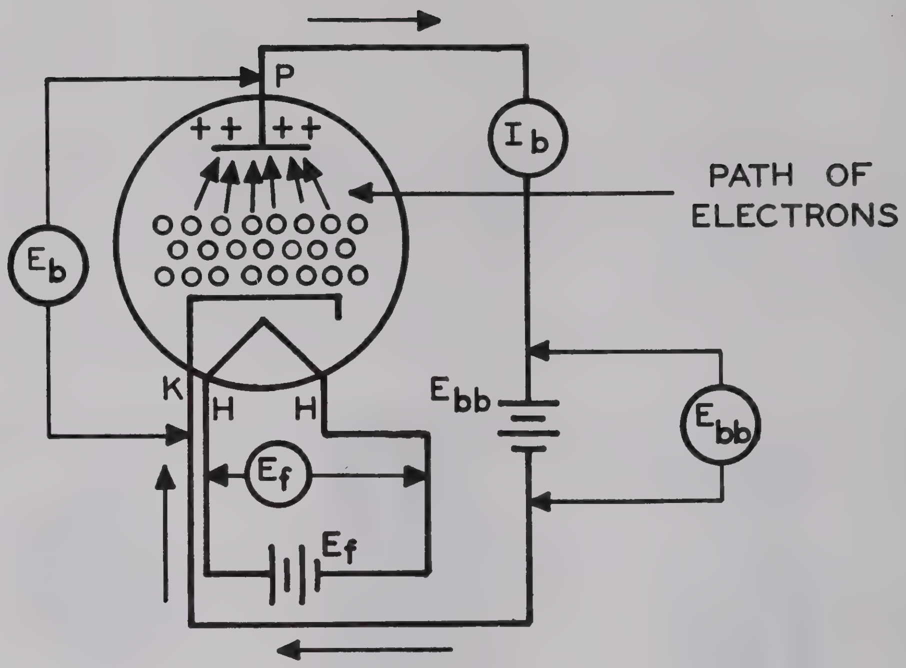


Figure 22

current I_b is measured by placing the meter in series in the plate circuit. Heater voltage E_f and plate supply voltage E_{bb} are measured by connecting voltmeters across the batteries.

The number of electrons drawn to the plate from the space charge depends on the plate voltage, E_b. As the plate voltage increases, the plate current, I_b, increases until the plate collects all the electrons given off by the emitter.

When the maximum plate current value is reached (all emitted electrons are attracted to the plate), a further increase in the plate voltage does not cause any further increase of plate current at the given emitter temperature. This maximum current is called SATURATION CURRENT, and the plate voltage that produces it is called SATURATION VOLTAGE. Since plate current does not increase after saturation voltage has been reached, this condition is known as PLATE SATURATION. This means that the emitter is not supplying electrons as fast as the positive plate can take them away from the space charge.

When the plate voltage is not changed, but the emitter temperature is increased by increasing the heater voltage E_f, more electrons are emitted. This increases the number of electrons in the space charge. With more electrons available, more are attracted to the plate. Thus, the plate current, I_b, increases, even though the plate voltage, E_b, stays the same.

However, when the emitter reaches a certain temperature, the repelling force of the negative space charge stops any further increase in emission. For a given plate voltage, the emitter temperature above which the plate current does not increase is called the SATURATION TEMPERATURE. This condition is known as CATHODE SATURATION. The plate is not positive enough to attract the extra electrons supplied by the emitter.

Since a diode tube allows plate current only when the plate is more positive than the emitter, the tube acts like a one-way valve. When the plate is positive with respect to the emitter, there is an electron flow from emitter to plate; but when the plate is negative, the electrons are repelled by the plate and the tube does not conduct. If the negative voltage is too large, the tube arcs over. The maximum negative voltage that the tube can stand without danger of arc-over is called the PEAK INVERSE VOLTAGE.

A resistor labeled R_L is connected between the cathode of tube V and the negative terminal of plate supply E_{bb} in Figure 23A. Since we are concerned only with the plate circuit of tube V, the complete heater circuit is not shown. However, it is assumed that the heater leads H-H are connected to a battery and, therefore, the cathode is hot and emitting electrons.

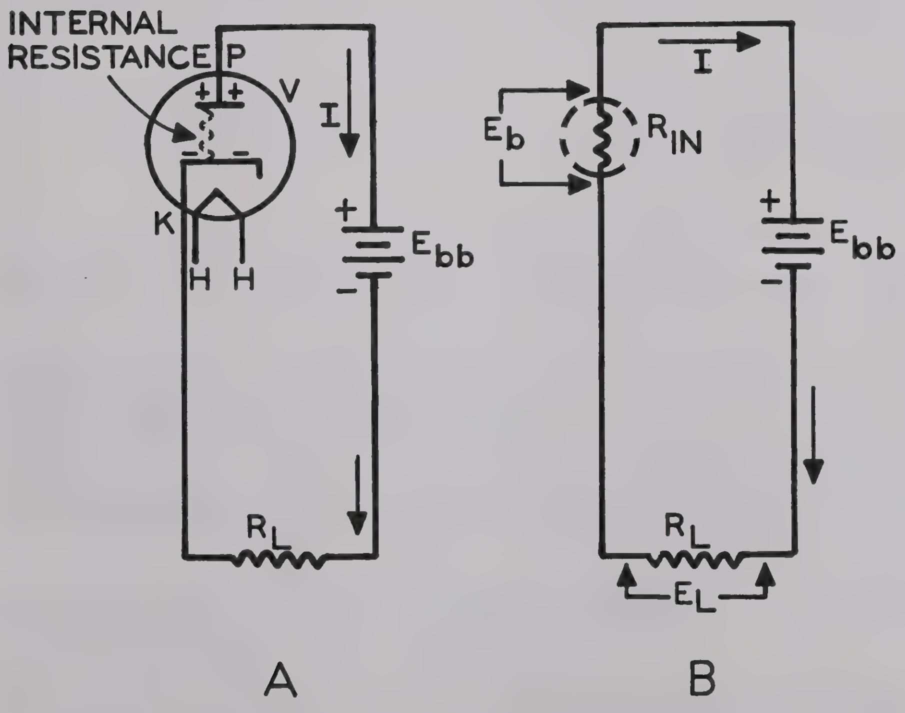


Figure 23

The plate of tube V is connected to the positive terminal of the battery. Therefore, the tube is conducting. Electrons from the space charge are attracted to the plate, pass through the battery and resistor R_L to the cathode, and from the cathode to the space charge, completing the circuit. Even though the space between the cathode and plate is nearly a vacuum, it has resistance as shown in Figure 23A. This resistance is called the INTERNAL RESISTANCE of the diode.

The electrical action of Figure 23B is the same as the electrical action of Figure 23A. Therefore, Figure 23B is called an EQUIVALENT CIRCUIT for Figure 23A. The dashed line circle in Figure 23B stands for the diode envelope. In each circuit, current I has only one path from the negative terminal of E_{bb} through R_L and the internal resistance of the tube (labeled R_{in} in Figure 23B), and back to the positive terminal of E_{bb}.

In a series circuit, the voltages across the separate parts of the circuit must add up to the supply voltage. The voltage across internal resistance R_{in} is labeled E_b and the voltage across R_L is labeled E_L in Figure 23B. The sum of E_b and E_L must equal the battery voltage, E_{bb}.

In most circuits, external resistance R_L is several times greater than internal resistance R_{in}. As an example, assume R_{in} is 100 ohms and R_L is 900 ohms. The total resistance of the series circuit R_{in} and R_L is $100 + 900$, or 1000 ohms. In percent, R_{in} is $(100/1000) \times 100\%$, or 10% of the total resistance.

Since voltage and resistance are directly proportional, R_L has 90% of the battery voltage across it. If the battery voltage is 100 volts:

E_L is 90% of 100 volts, or 90 volts;

E_b is 10% of 100 volts, or 10 volts.

As shown by this example, most of the battery voltage is across R_L in Figure 23. However, if the battery connections are reversed, the plate is more negative than the cathode and the diode no longer conducts. With no current in the circuit, the voltage, E_L, across resistor R_L is zero. If E_L is zero, the voltage, E_b, across R_{in} must equal the full 100 volts of E_{bb}.

DIODE CIRCUIT ACTION

Although semiconductor and tube diodes work in different ways they have one very important thing in common. They act as "one-way switches" to pass current in only one direction. On this basis, they are used to block one polarity of the alternations of an ac source.

Tube testers like this one can be used to test the operation of vacuum tube diodes as well as other types of vacuum tubes.

Courtesy Sencore

Alternating voltages occur very often in electronic systems. For example, commercial power companies use an alternating voltage which goes from positive to negative and back to positive again 60 times per second. AC generators are often used to operate the electronic circuits in airplanes. The output of these generators usually goes from positive to negative and back to positive again 400 times per second.

The voltage waveform of an ac generator is shown in Figure 24A. Starting at zero, it builds up to a maximum or "peak" of 3 volts in 2.5 seconds and falls to zero at the end of 5 seconds. Then, the voltage reverses polarity and builds up to a maximum negative of 3 volts at the end of 7.5 seconds and reduces to zero at the end of 10 seconds. Another cycle of the ac voltage is also shown from 10 seconds to 20 seconds.

Figure 24B shows how a diode rectifies or changes this type of alternating voltage to a series of pulses of one polarity only, or a pulsating dc voltage.

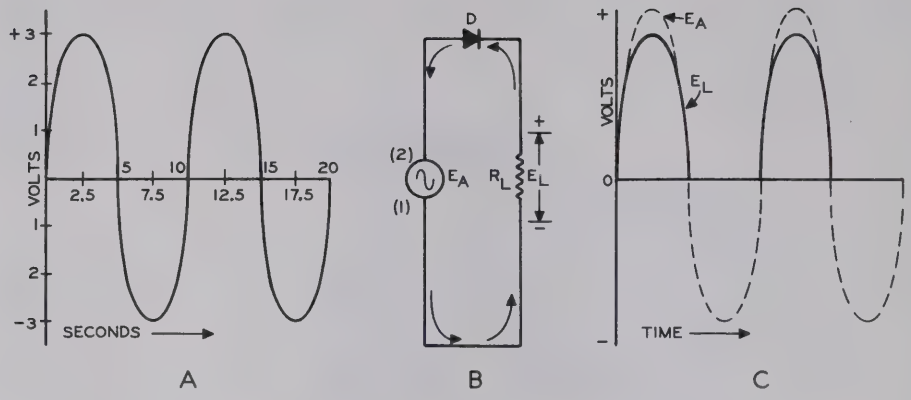


Figure 24

The alternating voltage source is represented by a waveform enclosed in a circle and labeled E_A. Resistor R_L represents the load or circuits to which the pulsating dc voltage is applied.

In operation, the alternating voltage, E_A, makes the anode of the semiconductor diode, D, alternately positive and negative with respect to the cathode. When E_A makes the anode positive, the diode conducts and VOLTAGE E_L IS DEVELOPED ACROSS RESISTANCE R_L. The polarity of E_L is indicated by the "+" and "—" signs. When E_A makes the anode of the diode negative, the diode does not conduct. With no current in the circuit, THERE IS NO VOLTAGE ACROSS R_L. Because the diode allows current only in the direction of the arrows, the voltage across R_L never reverses polarity.

Figure 24C shows the waveform of voltage across R_L. The dashed line curve shows the changes of E_A with respect to point 1 in Figure 24B. Also, with respect to this point, the solid line curve shows that E_L is a series of positive pulses with the same shape as the positive portions of the E_A waveform.

Because a small amount of E_A is dropped across semiconductor diode D, the voltage E_L is slightly less than the positive portions of E_A. This is shown in Figure 24C by drawing the solid line waveform for E_L slightly below the dashed line waveform for E_A.

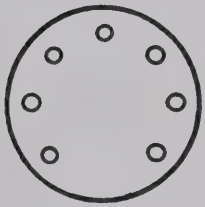
In Figure 24, a semiconductor diode serves as a rectifier. The results would be the same if a vacuum tube diode replaced the semiconductor. The waveform of Figure 24C would appear across the load resistance, because the tube conducts only on those supply alternations that make its plate positive with respect to its cathode.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

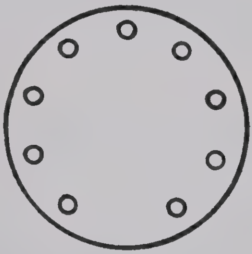
THE VACUUM TUBE DIODE

DIODE CIRCUIT ACTION

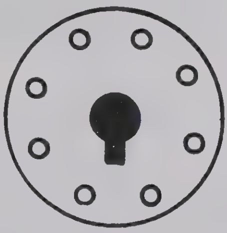
42. Shown below are bottom views of a 7-pin miniature tube, a 9-pin miniature tube and an octal tube. Number the pins in each view.



A

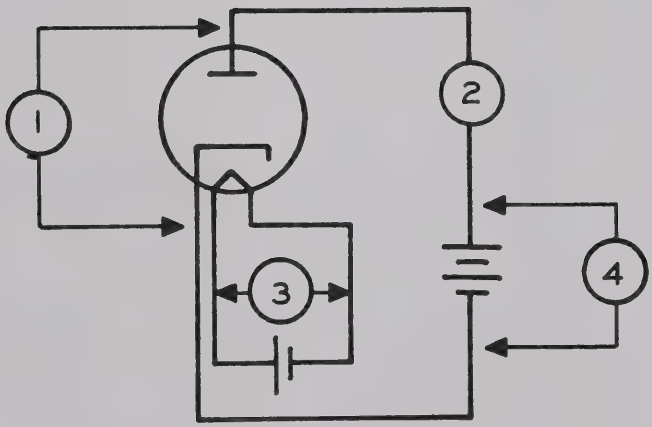


B



C

43. In the circuit below, describe what each of the dc meters shown measures in the circuit.



44. When a further increase of plate voltage or a further increase of heater voltage on a diode causes no further increase of plate current, (a) the tube is no good, (b) the battery is worn out, (c) the tube has reached saturation.

45. A diode may be compared to (a) a valve, (b) a battery, (c) a conductor.

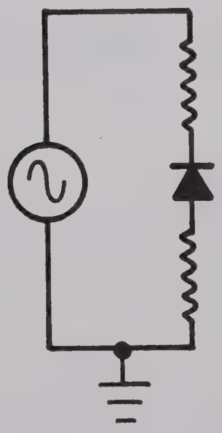
46. The maximum negative voltage that can be applied to the anode of a diode without danger of arc-over is called (a) arc voltage, (b) saturation voltage, (c) peak inverse voltage.

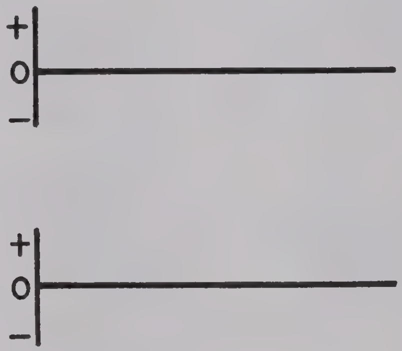
47. The internal resistance of a diode is always infinitely high because the space between the cathode and plate is nearly a vacuum. True or False?

48. Diodes are used to block ____________________________ the alternation of an ac source.

49. What does it mean when you say you have 60-Hz line voltage?

50. In the circuit below, draw the output waveform across each resistor when the ac generator applies a sinewave voltage to the diode circuit. (Hint — draw arrows to indicate direction of current flow and show polarities across the resistors.)





SUMMARY

There are two types of diodes: Semiconductor diodes and vacuum tube diodes. Both types allow current to pass through them in one direction only.

In the semiconductor diode, an N-type material and a P-type material are bound closely together. Electrons flow easily from the N-type material to the P-type material when an external voltage source of the proper polarity is applied. However, very few electrons flow if the polarity of the source voltage is reversed.

This property allows semiconductor diodes to rectify an alternating voltage. The diode conducts on one alternation to develop a voltage across a resistor or load. But, on the other alternation, the diode does not conduct and no load voltage is developed.

The vacuum tube diode can also be used to rectify an alternating voltage. In a vacuum tube, electrons may be emitted by a heated emitter (filament or cathode) and collected by a positive plate (anode). Because the plate normally does not emit electrons, the vacuum tube conducts in one direction only.

IMPORTANT DEFINITIONS

ACCEPTOR — A type of impurity that accepts or takes electrons from the atoms of a semiconductor substance.

ANODE — In a diode, the electrode that must be positive with respect to the cathode to allow the diode to conduct. The plate of an electron tube.

CATHODE — In a diode, the electrode that must be negative with respect to the anode (plate) to allow the diode to conduct.

DIODE — Any two-electrode device that conducts in only one direction.

DONOR — A type of impurity that adds electrons to the atoms of a semiconductor substance.

ELECTRODE — An element of an electron tube or semiconductor device that takes part in conduction, such as the plate, anode, cathode and filament.

ELECTRON EMISSION — The escape of electrons from certain materials.

ELECTRON TUBE — An arrangement of two or more conductive elements, enclosed in an envelope, to control electron flow in a circuit.

ELEMENT — Any of the electrical parts of an electron tube such as the filament, cathode or plate.

FILAMENT — In a directly heated electron tube, a heating element which also serves as the emitter.

FORWARD BIAS — A dc voltage applied to a PN junction semiconductor so that the positive terminal of the voltage source connects to the P-type material and the negative terminal to the N-type material. It produces forward current in the circuit.

FORWARD CURRENT — Current in a circuit of a semiconductor device due to conduction by majority carriers across the PN junction.

HEATER — In an indirectly heated electron tube, the element that supplies heat to the cathode.

HOLE — In a crystal lattice, a point which has been vacated by an electron.

INTRINSIC — A word used to indicate a semiconductor that has no impurities.

IMPORTANT DEFINITIONS (Continued)

JUNCTION DIODE — A diode consisting of a PN junction and suitable connecting leads.

MAJORITY CARRIERS — The type of current carriers, free electrons or holes, of which a given semiconductor contains the most.

MINORITY CARRIERS — The type of current carriers, free electrons or holes, of which a given semiconductor contains the least.

N-TYPE SEMICONDUCTOR — A doped semiconductor in which the majority current carriers are electrons.

PEAK INVERSE VOLTAGE — In an electron tube, the maximum negative voltage that can be applied to the plate without danger of arc-over. In a semiconductor diode, the maximum reverse bias voltage that can be applied without reaching the zener (or breakdown) voltage.

PLATE — In an electron tube, the electrode that must be positive with respect to the cathode to allow the tube to conduct. Also called the ANODE.

PLATE CURRENT — In an electron tube, the electron flow from cathode to plate. In the external plate circuit, the electron flow from the plate, through the circuit, to the cathode.

PLATE VOLTAGE — In an electron tube, the difference of potential between plate and cathode.

PN JUNCTION — A junction between an N-type semiconductor and a P-type semiconductor made by some method such as diffusing, fusing or melting.

P-TYPE SEMICONDUCTOR — A doped semiconductor in which the majority current carriers are holes.

RECOMBINATION — The action by which current carriers (electrons and holes) combine and cancel each other.

RECTIFICATION — The conversion of ac to pulsating dc.

RECTIFIER — A device which converts ac to pulsating dc.

REVERSE BIAS — A dc voltage applied to a PN junction so that the positive terminal of the voltage source connects to the N-type material and the negative terminal to the P-type material. It produces reverse current in the circuit.

IMPORTANT DEFINITIONS (Continued)

REVERSE CURRENT — Current in a circuit of a semiconductor device due to conduction by minority carriers across the PN junction.

SEMICONDUCTOR — A substance having conductive ability greater than that of an insulator but less than that of a good conductor.

SPACE CHARGE — In an electron tube, a cloud of free electrons surrounding the emitter.

THERMIONIC EMISSION — The liberation of electrons from a solid metal as a result of heat (thermal energy).

VACUUM TUBE — A form of electron tube in which the envelope contains a vacuum, as opposed to a gas-filled electron tube, in which gases are pumped into the envelope after the air is removed.

ZENER DIODE — A junction diode designed to operate in the reverse bias region.

PRACTICE EXERCISE SOLUTIONS

1. (c) diode.
2. an alternating voltage or an ac voltage — A voltage which does not change polarity is called a direct voltage or dc voltage.
3. rectification — The device, usually a semiconductor or electron tube, that does the rectifying is called a rectifier.
4. (a) has few free electrons. — A conductor has many free electrons and a semiconductor has a crystalline or lattice structure.
5. True — As a result, under normal conditions a semiconductor is neither a good conductor nor a good insulator.
6. free — Free electrons are high-energy electrons not bound tightly to atoms.
7. hole
8. (d) positive.
9. True — In a conductor, free electrons wander between atoms to form a current flow. This is also true in a semiconductor, but in addition to this flow, bound electrons jump from hole to hole within the lattice. In effect, these atom-jumping electrons cause a hole flow in a direction opposite to that of the free electron flow.
10. False — Holes move at about half the speed of free electrons at the same applied voltage. Atom-jumping bound electrons, which cause hole movement, cannot move as fast as free electrons.
11. An intrinsic semiconductor is a crystal without impurities.
12. (c) has added impurities. — The impurities in a doped semiconductor increase either the holes or the free electrons so that the material will conduct at room temperature.
13. (a) N-type. — The N refers to the negative polarity of the excess free electrons. The P in P-type semiconductor refers to the positive polarity of excess holes.
14. True — This is exactly reversed in the P-type semiconductor.
15. False — When the holes within the semiconductor reach the negative terminal, they combine with electrons entering the material at this terminal. Only electron flow is possible outside of the semiconductor material.

PRACTICE EXERCISE SOLUTIONS (Continued)

16. free electrons; holes

17. Recombination occurs when a hole and an electron meet and combine with each other. When this happens, both cease to be current carriers.

18. The PN junction between the N-type and P-type semiconductors forms a semiconductor diode.

19. True — As a result, a small potential is produced across the junction.

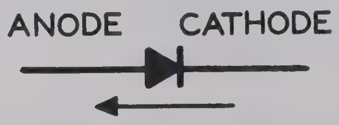
20. (c) a potential hill.

21. (a) a power supply. — With energy supplied by a power supply, such as a battery, holes and electrons gain sufficient energy to overcome the potential hill and cross over the junction as a current.

22. P; N

23. False — Minority carrier conduction is called reverse current because it is caused by reverse bias. Forward current by majority carriers is caused by forward bias.

24.



25. (b) a junction formed by a wire pressing on a piece of semiconductor material.

26. (b) hole injection.

27. True

28. red

29. The blocking layer.

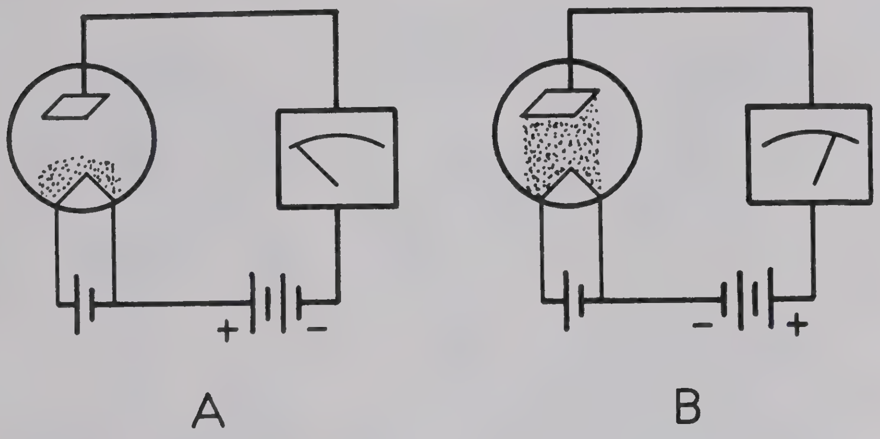
30. (c) thermionic emission. — The word thermionic means the emission was caused by thermal or heat conditions.

31. positive — The negative charge on the electrons caused them to be attracted towards the positive plate, since unlike charges attract. A negative plate repelled the negative electrons, preventing current flow.

PRACTICE EXERCISE SOLUTIONS (Continued)

32. space charge

33.



34. directly

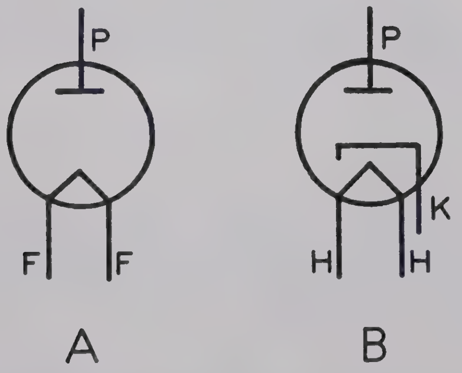
35. indirectly

36. heater — We prefer to use the word filament to mean the directly heated type of emitter.

37. False — The electrons are emitted by the cathode which is kept at a high temperature by the heater.

38. plate

39.

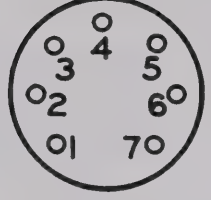


40. (b) the temperature (lower than for pure tungsten wire) causes the thorium to reach the filament surface.

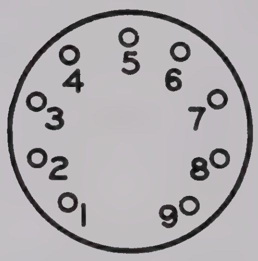
PRACTICE EXERCISE SOLUTIONS (Continued)

41. (a) is relatively steady. — Heater ac voltage alternations do not cause great changes in cathode temperature.

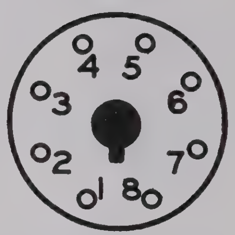
42.



A



B



C

From a bottom view, all tube base pins are numbered in a clockwise direction. In diagrams A and B, the first and last pins are those separated by the wide space. In diagram C, the key points between the first and last pins.

43. Meter 1 measures E_b, the average plate voltage.
Meter 2 measures I_b, the average plate current.
Meter 3 measures E_f, the heater voltage.
Meter 4 measures E_{bb}, the plate supply voltage.

44. (c) the tube has reached saturation. — This is a normal condition and does not indicate a defective tube or battery.

45. (a) a valve. — A diode conducts when its plate is positive with respect to its cathode, but it is cut off when the voltages are reversed. It therefore acts like a valve or a switch.

46. (c) peak inverse voltage.

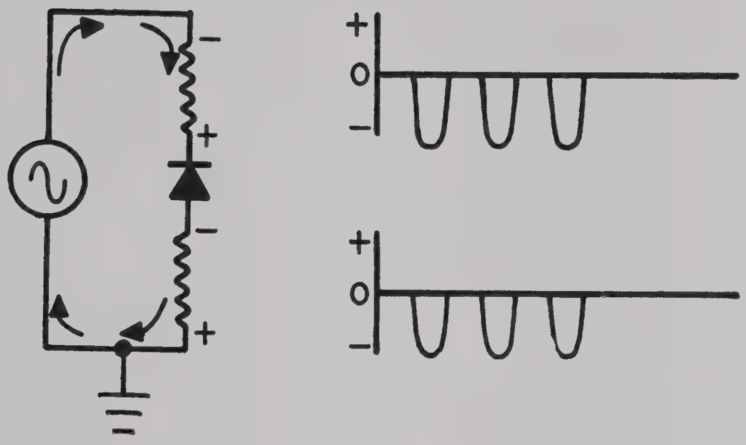
47. False — When the plate of a diode is positive with respect to its cathode, electrons pass through the vacuum from cathode to plate and the internal resistance is relatively low.

48. one polarity of — A diode may be made to block all negative alternations of the ac source or, by reversing the diode, it may block all positive alternations.

PRACTICE EXERCISE SOLUTIONS (Continued)

49. **By 60-Hz line voltage, we mean the alternating voltage obtained from the power line goes from positive to negative and back to positive again 60 times per second.**

50.



Note that electron current flows easily from the diode cathode to the diode anode (from the bar to the triangle of the diode symbol), so that current will be in the direction of the arrows shown above. This current can only flow when the lower generator lead is more positive than the upper lead. Any voltage appearing across either resistor is of the polarity shown at that resistor and varies as shown by the two drawings at the right.

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1025A
EXAMINATION CHECK SHEET

1025A

1. D - IN THE ATOMS OF A SEMICONDUCTOR CRYSTAL LATTICE, A HOLE IS A -- POINT WHICH AN ELECTRON HAS VACATED.
The hole is considered to be positive since it represents the absence of an electron.

2. A - IN AN N-TYPE SEMICONDUCTOR, THE MAJORITY CURRENT CARRIERS ARE -- FREE ELECTRONS.
When the donor material is added to the pure semiconductor to make N-type material, free electrons are produced.

3. C - AN IMPURITY THAT ADDS ELECTRONS TO A SEMICONDUCTOR IS CALLED -- A DONOR.
The donor impurity adds electrons whereas the acceptor impurity produces the absence of electrons, or holes.

4. A - WITH REFERENCE TO SEMICONDUCTORS, THE TERM RECOMBINATION DESCRIBES THE ACTION IN WHICH -- AN ELECTRON AND A HOLE COMBINE.
Since the hole and electron have opposite polarities, they combine when brought together.

5. D - IF A BATTERY IS CONNECTED WITH ITS NEGATIVE TERMINAL TO THE P-TYPE MATERIAL AND ITS POSITIVE TERMINAL TO THE N-TYPE MATERIAL OF A SEMICONDUCTOR DIODE, -- THE DIODE IS REVERSE BIASED.
When the P-Type material is made positive and the N-type material is made negative, the diode is forward biased.

6. D - AROUND THE EMITTER OF AN ELECTRON TUBE THERE IS A SPACE CHARGE MADE UP OF -- ELECTRONS.
Since the space charge is made up of electrons, it has a negative charge.

7. C - WHEN THE VACUUM TUBE DIODE OF FIGURE 16 CONDUCTS, THE ELECTRON FLOW INSIDE THE TUBE IS FROM -- THE CATHODE TO THE PLATE.
Electron flow is always from the most negative point (cathode) to the most positive point (plate).

8. C - RECTIFICATION IS THE PROCESS IN WHICH -- AC IS CONVERTED TO PULSATING DC.
Since diodes usually perform the task of converting ac to pulsating dc, they are often called rectifiers.

9. A - IN THE BASIC RECTIFIER CIRCUIT OF FIGURE 24B, THERE IS A VOLTAGE ACROSS R_L ONLY WHEN -- DIODE D CONDUCTS.
When the diode is non-conductive, no voltage appears across R_L and all of the supply voltage appears across the diode.

10. A - WHAT CONSTRUCTION FEATURE OF THE MINIATURE TUBE INSURES PROPER POSITIONING OF THE PINS IN A TUBE SOCKET? -- A GAP BETWEEN TWO OF THE PINS.
The pins are numbered starting from the aligning gap or key in a clockwise direction (bottom view).

E.W. NOV 18 '76

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1025A

Example: An electric fan

A ☐
B ■
C ☐
D ☐

A. supplies water. B. blows air. C. detects smoke. D. sharpens pencils.

1. A ☐ B ☐ C ☐ D ☒

In the atoms of a semiconductor crystal lattice, a hole is a
(A) negative atom. (B) free electron. (C) point in which an electron is located. (D) point which an electron has vacated.

2. A ☒ B ☐ C ☐ D ☐

In an N-type semiconductor, the majority current carriers are
(A) free electrons. (B) positive atoms. (C) holes. (D) electrons that are tightly bound to the nucleus of the atom.

3. A ☐ B ☐ C ☒ D ☐

An impurity that adds electrons to a semiconductor is called
(A) a free electron. (B) a P-type semiconductor. (C) a donor. (D) an acceptor.

4. A ☒ B ☐ C ☐ D ☐

With reference to semiconductors, the term recombination describes the action in which
(A) an electron and a hole combine. (B) a diffused PN junction is produced. (C) an impurity is added to an intrinsic semiconductor. (D) a grown PN junction is produced.

5. A ☐ B ☐ C ☐ D ☒

If a battery is connected with its negative terminal to the P-type material and its positive terminal to the N-type material of a semiconductor diode,
(A) the battery voltage overcomes the potential hill. (B) the diode conducts a large forward current. (C) the junction resistance is low. (D) the diode is reverse biased.

6. A ☐ B ☐ C ☐ D ☒

Around the emitter of an electron tube, there is a space charge made up of
(A) holes. (B) molecules. (C) atoms. (D) electrons.

7. A ☐ B ☐ C ☒ D ☐

When the vacuum tube diode of Figure 16 conducts, the electron flow inside the tube is from
(A) the cathode to the heater. (B) the heater to the cathode. (C) the cathode to the plate. (D) the plate to the cathode.

8. A ☐ B ☐ C ☒ D ☐

Rectification is the process in which
(A) the plate is made positive with respect to the anode. (B) dc is converted to ac. (C) ac is converted to pulsating dc. (D) the heater of an indirectly heated tube emits electrons.

9. A ☒ B ☐ C ☐ D ☐

In the basic rectifier circuit of Figure 24B, there is a voltage across R_L only when
(A) diode D conducts. (B) diode D does not conduct. (C) there is no current. (D) the anode of D is negative.

10. A ☒ B ☐ C ☐ D ☐

What construction feature of the MINIATURE TUBE insures proper positioning of the pins in a tube socket?
(A) A gap between two of the pins. (B) An aligning plug. (C) A key guide. (D) Evenly spaced base pins.

GUIDE SHEETS FOR EXPERIMENTS
9502 SERIES

ACTIVE AND PASSIVE CIRCUITS

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MATERIALS

THIS LIST INCLUDES ALL TOOLS, HARDWARE AND ELECTRONIC COMPONENTS NEEDED TO COMPLETE THE EXPERIMENTS IN THIS MANUAL.

1 - Pair Long-Nose Pliers

1 - Pair Wire Cutters

1 - Low Wattage Soldering Iron (30 W to 75 W)

1 - Multimeter and Test Leads

2 - Test Prod Spring Adapters

1 - Design Console

1 - Battery (9 Volt)

1 - Battery Clip

1 - Printed Circuit Board

1 - Electromagnetic Coil

- Modular Connectors

1 - Permanent Magnet

2 - Diodes

1 - 10Ω, 1 W, Resistor

1 - 1 kΩ, 1/2 W, Resistor

1 - 3.9 kΩ, 1/2 W, Resistor

1 - 4.7 kΩ, 1/2 W, Resistor

2 - 10 kΩ, 1/2 W, Resistors

1 - 22 kΩ, 1/2 W, Resistor

1 - 100 kΩ, 1/2 W, Resistor

2 - 10 μF Capacitors

1 - 1000 μF Capacitor

- Hookup Wire

- Solder

INTRODUCTION

PART 1

SAFETY

In all the preceding experiments, the voltages encountered have been very low. Starting with this section you will be measuring and working with much higher voltages, and therefore more dangerous. As a technician you will be required to work with high voltages. You should therefore become quite familiar with the safety procedures so you can minimize the danger of working with high voltages.

Most beginners have little difficulty with high voltages because of one fact: they are careful. Electricity is very patient and it will wait indefinitely for an individual to make a mistake. The first rule when working with the circuits is to be careful and aware of what you are doing. Treat all electrical devices with respect. Carelessness causes more mishaps than any other single cause.

Anytime you are working on electrical devices, avoid damp areas. Work on dry floors or use rubber mats, and dry your hands thoroughly before working on a circuit. Water or perspiration on your hands reduces your skin resistance, and thus allows more current to flow should you come in contact with a source of voltage.

When measuring voltages, do not touch the metal end of the test prods. Also avoid touching the chassis of a unit with one hand while working with a circuit with the other hand. Circuits can be completed through set screws in knobs and other metal parts which may not be readily apparent.

When measuring quantities in a circuit, remove the test prods before changing the switch settings of the measuring device. Damage can be done to the meter if the switch is moved with the prod connected to an active circuit.

In summary:

1. Be careful.

2. Work in a dry area.

3. Avoid unnecessary contact with metal parts of the circuit.

4. Remove the test prods when changing the settings of a measuring device.

PART 2

SOLDERING

PARTS NEEDED

1 - Printed Circuit Board
1 - Pair of Long-Nose Pliers
1 - Pair of Wire Cutters
1 - Low Wattage Soldering Iron
- Solder
4 - 1" Pieces of Wire
3 - 1 1/2" Pieces of Wire

Before proceeding further, read the supplement on soldering. Good soldering is very important in electronics. Far more malfunctions in student constructed devices are caused by poor soldering than from any other cause.

PROCEDURE

1. Remove the insulation from 4 pieces of 1" wire and 3 pieces of 1 1/2" wire.

2. Insert the 1" wires between holes A and E, B and F, C and G, and D and H of the sample PC board (refer to Figure 1). Insert the wires from the blank side of the board. The ends of the wires will protrude through the foil side of the board, as shown in Figure 2. Spreading the wire slightly will help to hold the wire in place.

3. Solder each wire to the PC board and cut off the excess lead length. Take care to prevent solder from running between holes E, F, G and H. Since holes A, B, C and D are connected with copper foil, accidental running of solder between these holes will cause no problems.

4. Insert the 1 1/2" wires between holes I and L, J and M, and K and N (refer to Figure 1).

5. Solder each of these wires, taking care that solder does not run between holes I, J and K.

6. When your sample PC board is complete, return it to us along with the form you will find in with the test material for your lab experiments. We will return the form to you, indicating whether or not the sample is satisfactory. YOU DO NOT HAVE TO WAIT FOR THE RETURN OF THE FORM TO CONTINUE THE EXPERIMENTS.

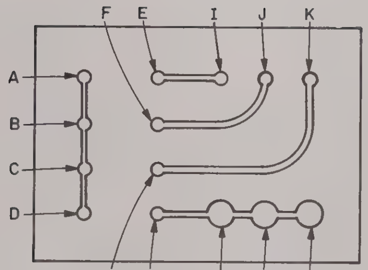

FIGURE I

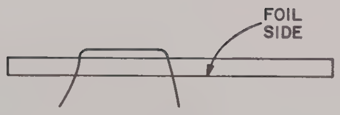

FIGURE 2

NOTES

EXPERIMENT 1

DIODES

PARTS NEEDED

1 - Design Console
1 - Multimeter and Test Leads
1 - Battery (9 Volt)
1 - Battery Clip
- Modular Connectors
1 - 10 kΩ, 1/2 W, Resistor
1 - Diode
2 - Test Prod Spring Adapters
- Hookup Wire

OBJECTIVE

The purpose of this experiment is to show the action of a diode and how an ac voltage can be converted to a dc voltage.

PART 1

PROCEDURE

1. Choose one of the diodes from your supply of parts. There are various configurations of the diode; however, the cathode of the diode is usually marked in some way. A pointed or a color banded end are common ways of identifying the cathode of a diode. Identify the cathode of the diode you have by looking for an identifying mark as indicated above.

2. Set up the circuit shown in Figure 1-1. Be sure the anode of the diode connects to the positive terminal of the battery.

3. Measure the voltage across the resistor. You should measure almost the full source voltage (9 volts).

4. Measure the voltage across the diode. You should measure very little voltage (less than one volt).

CONCLUSION

In this part we have forward biased the diode. When a diode is forward biased, very little voltage is developed across it. Most of the voltage applied must therefore appear across the resistor to satisfy Kirchhoff's Voltage Law.

PART 2

PROCEDURE

1. Set up the circuit shown in Figure 1-2. The diode is now reverse biased.

2. Measure the voltage across the resistor. You should measure very little voltage because of the reverse biased state of the diode.

3. Measure the voltage across the diode. You should measure almost the full source voltage.

CONCLUSION

In this part the diode is reverse biased and appears as an open. Very little current flows in the circuit, and the voltage across the resistor is very low. The diode voltage is almost equal to the source voltage. The actual voltage across the resistor and the diode depends on the amount of reverse current flowing.

PART 3

PROCEDURE

1. Set up the circuit shown in Figure 1-3. A suggested layout is shown in Figure 1-4.

2. Be sure the on/off switch of the console is turned fully counterclockwise before plugging the console into a convenient wall outlet.

3. Move the on/off switch one position clockwise, and measure the ac voltage between points A and B as shown in Figure 1-3. You should measure between 7 and 8 volts.

4. Now measure the dc voltage between points A and B. You should measure zero volts since there is no dc voltage between these points.

5. Measure the dc voltage across the 10 kΩ resistor. You should measure about 3 volts dc. Turn the design console on/off switch to the off position.

CONCLUSION

In the circuit used for Part 3, we have applied an ac voltage to points A and B. This voltage is then converted to a dc voltage because of the action of the diode. The circuit (as shown) is not highly efficient; however, there are methods of increasing the dc output, as we will learn later.

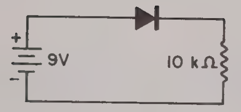

FIGURE 1-1

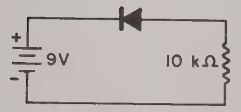

FIGURE 1-2

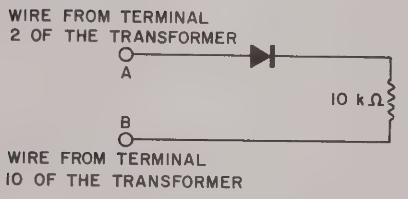

FIGURE 1-3

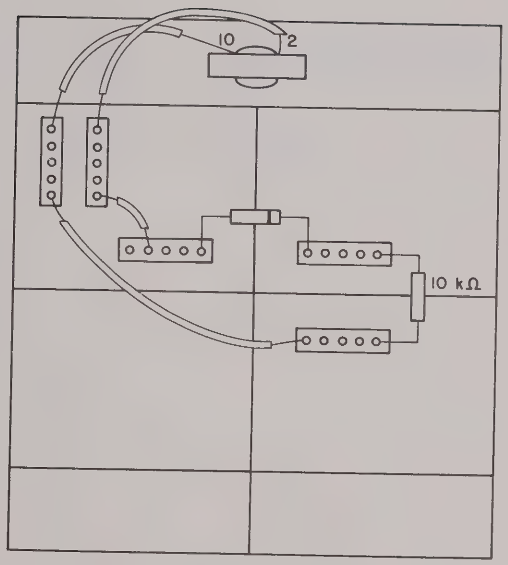

FIGURE 1-4

NOTES

THIRD CLASS MAIL ENCLOSURE

QUESTION SHEETS FOR LABORATORY SHIPMENTS ELI-2 AND ELI-3

PRINTED IN U.S.A.

NAME ______________________________

ADDRESS ______________________________

CITY ______________________________

STATE ______________ ZIP CODE ______________

Fold on this line

STUDENT NUMBER ______________

☐ Sample satisfactory.

☐ Sample unsatisfactory. Please use enclosed PC board and resubmit your sample. Return this form with the new sample.

Fold on this line

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4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

9502-1A
EXAMINATION CHECK SHEET

1. B - A DIODE CAN BE USED TO -- CONVERT AC TO DC.
The diode is not capable of amplifying and will not convert dc to ac. It does, however, convert ac to dc.

2. C - IF THE ANODE OF A DIODE IS POSITIVE WITH RESPECT TO THE CATHODE, -- THE DIODE IS FORWARD BIASED.
When the anode is positive with respect to the cathode, it will conduct. This is the forward biased condition.

3. D - IF THE DIODE IS FORWARD BIASED BY A BATTERY, THE VOLTAGE ACROSS A RESISTOR IN SERIES WITH THE DIODE WILL BE -- ALMOST EQUAL TO THE BATTERY VOLTAGE.
With the diode forward biased the voltage across the diode will be very low. Hence, the voltage across the resistor will be the total source voltage minus the small voltage across the diode when it is forward biased.

4. A - WHAT IS THE VOLTAGE ACROSS THE DIODE IF IT IS FORWARD BIASED BY A BATTERY? -- VERY LOW - ALMOST ZERO.
When the diode is forward biased the voltage across the diode is at a minimum - very close to zero.

5. C - TO REVERSE BIAS A DIODE, -- THE ANODE MUST BE MADE NEGATIVE WITH RESPECT TO THE CATHODE.
Reverse bias is opposite to forward bias. Reverse bias conditions are that the anode is negative with respect to the cathode.

MAGNETS AND ELECTROMAGNETS

1028

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Many of the devices we commonly use employ electromagnets of one form or another. For example, the motors in the above tape recorder are basically electromagnets. Likewise, the "heads" which record and play back the information on the tape are basically electromagnets.
Courtesy Superscope Inc.

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> *If you wish your merit to be known, acknowledge that of other people.*
>
> *— Oriental Proverb*

MAGNETS AND ELECTROMAGNETS

Magnets and electromagnets have many uses—every electric motor and generator requires a magnetic field for its operation. With the exception of a few special types, all use electromagnets. Mounted on cranes and hoists, large electromagnets are used to lift heavy pieces of iron or steel. These magnets can hold several tons of metal and are used in foundries, machine shops and steel mills for loading and unloading cars, or moving metals to various parts of the shop.

Magnets are found in practically every electronic application. For instance, in a small table model radio there is at least one magnet, and in a color television set there may be more than a dozen. Many headphones and loudspeakers have electromagnets, and variations in the strength of the magnetic field cause the headphone diaphragm or speaker cone to vibrate and set up sound waves which produce the voice or music being broadcast.

MAGNETIC MATERIALS

The properties of **MAGNETISM** were known to the Greeks as early as 700 B.C. It was found that a certain type of ore had the power to attract pieces of iron which were in its vicinity. The discovery was made in a province called Magnesia, and the ore was given the name **MAGNETITE** after its place of discovery. The type of magnetite which exhibits magnetic properties is commonly known as Lodestone. Any material which exhibits these magnetic properties is called a **MAGNET.**

The first uses of magnetism were recorded by the Chinese, who are believed to have used suspended pieces of magnetite as compasses nearly 2000 years ago. Compasses were also used by the European navigators, but not until about 1200 A.D. Christopher Columbus was interested in the properties of magnetic compasses, and he made some important observations on the accuracy of compasses during his voyage to America in 1492. However, the first true study of magnetic properties was not attempted until 1600, when William Gilbert, an English physician, published a report on his experiments with magnets.

A careful and thorough study of magnets and their actions shows that all materials are affected to some extent when brought close to a strong magnet. By testing all the known substances, it has been found that iron and steel are affected very strongly, cobalt and nickel are affected to some extent, while all other materials are affected only slightly. Iron and steel are called magnetic, or ferromagnetic, substances, the prefix "ferro" being taken from the Latin word "ferrum," which means iron.

The magnetic effect on iron is so much greater than on cobalt and nickel that iron is the only magnetic element which, by itself, is of commercial importance. However, certain combinations or alloys of iron, cobalt and nickel are in common use because of certain advantages in one application or another.

Natural Magnets

Any magnet found in a natural state is known as a **NATURAL MAGNET.** Deposits of magnetic ore (magnetite) have been discovered at various places, one of the largest being in Labrador. Pieces of this magnetic ore are called natural magnets because they exhibit the properties of magnetism without any special treating. The earth itself is considered to be a huge natural magnet because it possesses the same properties as smaller magnets.

Artificial Magnets

Due to irregularities in size, shape and strength, natural magnets have little commercial value. However, when placed in a magnetic field, a piece of steel becomes a magnet. By proper treatment called aging, it can be made to keep its magnetism almost indefinitely. When properly magnetized and treated, a piece of steel is called a **PERMANENT MAGNET.**

Almost any kind of steel and certain types of ceramics can be made into a permanent magnet, but some of the alloys mentioned earlier can be more strongly magnetized than ordinary steel. The most popular magnetic alloys for permanent magnets are alloys of pure iron, aluminum, nickel and cobalt, called **ALNICO**. By combining different percentages of these metals, various magnetic qualities are set up in the alloys when they are processed in a magnetic field. Permanent magnets made of alnico are used commonly in television and radar equipment and in electronic measuring instruments. Ceramic magnets are finding wide use in loudspeakers and electronic instruments.

When in contact with a permanent magnet, a piece of soft iron becomes magnetized as strongly as a piece of steel. However, when the permanent magnet is removed, the iron loses practically all of its magnetism. Therefore, a piece of iron, especially soft iron, is called a **TEMPORARY MAGNET.** Because they do not occur in a natural state, all forms of magnetized steel and iron are considered as **ARTIFICIAL MAGNETS.**

MAGNETIC POLES

When a bar magnet is suspended or pivoted, it rotates to a generally north and south direction, with the same end always pointing toward the north. To illustrate this action, in Figure 1, a bar magnet is suspended by a string so that it swings freely. No matter which way it is pointed, when released, the magnet comes to rest pointing approximately north and south.

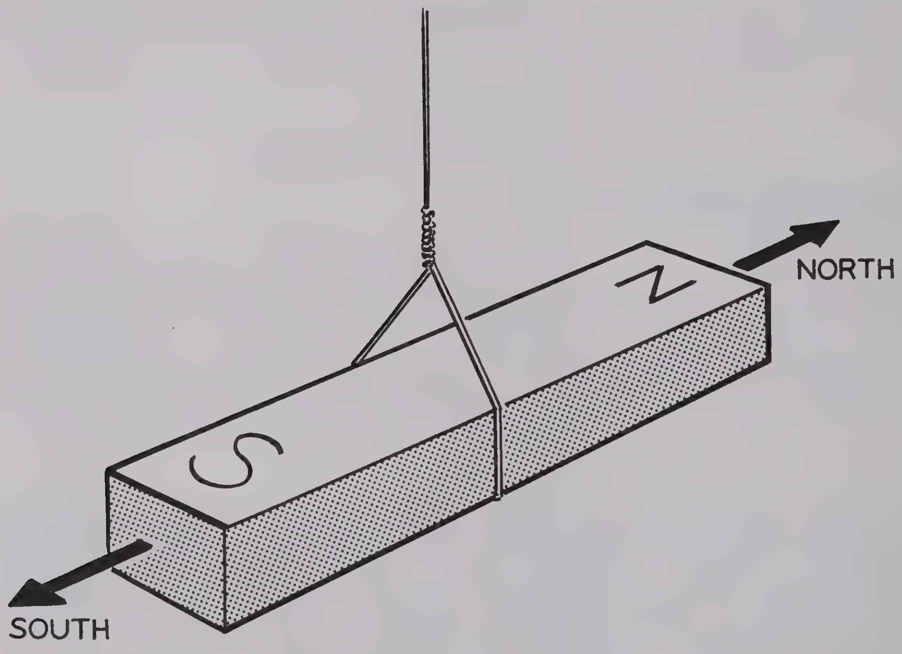


Figure 1

At each end of the bar magnet, there is a concentration of magnetic force. This concentration of force is known as a **MAGNETIC POLE**. The presence of the poles can be demonstrated by dipping the ends of a magnet into a pile of iron filings. When the magnet is withdrawn, filings cling to each end, as shown in Figure 2.

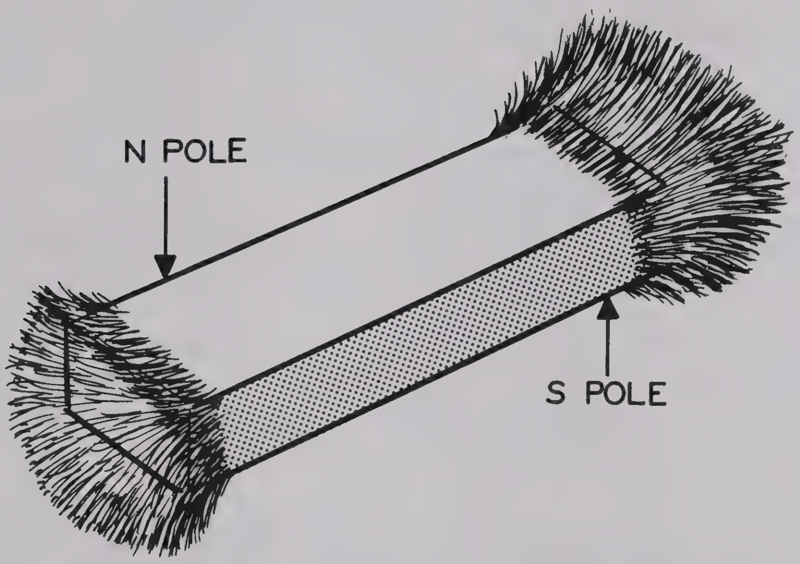


Figure 2

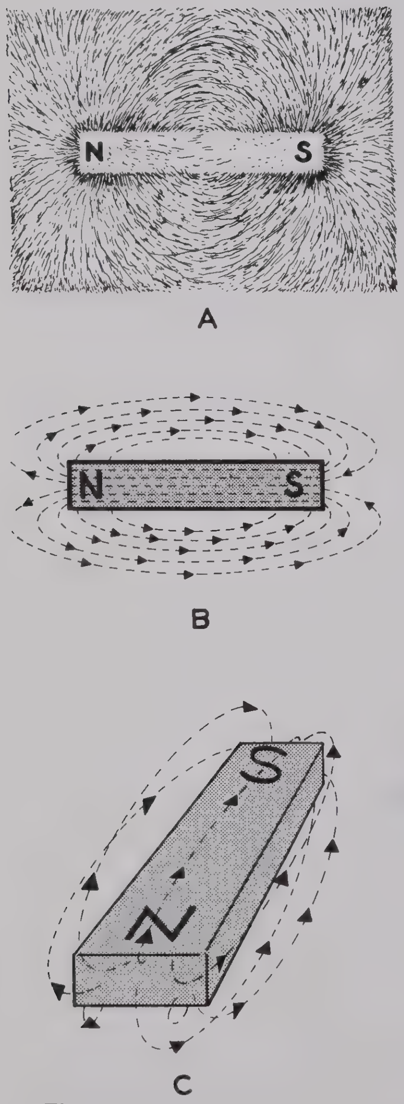
The poles of a bar magnet are named after the direction in which they point when the magnet is suspended. The end of the bar magnet that points toward the north is called the NORTH POLE, and the end that points toward the south, the SOUTH POLE. Whenever a permanent magnet has its ends marked N and S, these letters indicate its north and south poles.

MAGNETIC FIELDS

A magnet produces some surprising effects. When placed close to one end of a strong magnet, a small piece of iron such as a nail actually jumps a quarter of an inch or more to reach the magnet.

The fact that the iron jumps to the magnet shows very clearly that the magnetic effect extends for some distance around the magnet. This area of influence in the space around the magnet is known as the **MAGNETIC FIELD.** The unknown force that causes the field is referred to as the **MAGNETOMOTIVE FORCE (mmf)** of the magnet.

For convenience, a magnetic field is considered as being made up of magnetic lines of force, or simply **MAGNETIC LINES.** However, the single line of force is seldom considered in analyzing magnetic fields. Instead, it is more common to use the term **MAGNETIC FLUX,** which refers to the total number of magnetic lines that make up a magnetic field.



A

B

C

Figure 3

A simple but effective method of making a magnetic field "visible" is to place a piece of ordinary glass over a bar magnet and then sprinkle iron filings on the glass. The glass offers no opposition to the field, even though it is not a good conductor of magnetic lines. Thus, the filings are affected by the field, and align themselves in a pattern like that shown in Figure 3A.

Notice that these lines seem to extend between the north and south poles of the magnet. These lines of force are assumed to leave the N pole and enter the S pole. If fully drawn, each line forms a closed loop from N to S outside the magnet and from S to N within the magnet.

The magnetic field is shown more clearly in the diagram of Figure 3B. This is the usual method of sketching magnetic fields, since it is much simpler to draw a diagram of this type, and greater detail concerning the lines of force is possible. The dashed lines represent the magnetic lines, and the small arrowheads show the direction of these imaginary lines.

In thinking of these magnetic lines, just imagine that they are small, tightly stretched rubber bands. Rubber bands try to shorten or contract, and that is exactly what the magnetic lines try to do. Moreover, the lines of force crowd each other somewhat and try to push sidewise, but never touch. Figure 3C is a perspective drawing illustrating that the magnetic field is three dimensional; that is, entirely around the magnet. Although these magnetic lines extend indefinitely out into space, only those in the space near the magnet, where the effect is strong enough to be useful, are shown.

In addition to providing a convenient means of explaining the action of a magnetic field, the theoretical lines of force also provide a means of measurement. In practical work, magnetic fields have a comparatively large number of lines and are of all shapes and sizes. Therefore, they usually are described as having a certain number of lines per square centimeter, which means the number of lines that pass through each square centimeter of a surface that is placed squarely across the magnetic field.

Because a given number of lines of force may be spread over a comparatively large field or compressed into a relatively small field, it is necessary to know both the number of lines that make up the flux and the size of the area through which the lines of force pass. The number of lines passing through a given area is known as the density of the field or the **FLUX DENSITY.**

The standard unit of measurement of the number of magnetic lines of force or magnetic flux is the **WEBER,** abbreviated **Wb.** One weber is equal to 100,000,000 or 10^8 lines of force. The symbol used to represent magnetic flux is the Greek letter phi (ϕ). As previously mentioned, the number of lines of force passing through a given area is also important. The standard unit of measurement of the lines of force for a given area of the flux density is the **TESLA**. A tesla is equal to a weber per square meter; that is, 10^8 magnetic lines of force passing through an area one meter by one meter. The capital letter B is often used to represent flux density. The relationship between the weber and the tesla can be put in the form of a single formula as follows:

$$B = \frac{\phi}{m^2} \tag{1}$$

where: B = flux density in teslas,

ϕ = number of lines of force in webers, and

m^2 = the cross-sectional area of the magnetic path in square meters (one meter equals 3.28 ft.).

ATTRACTION AND REPULSION

Figure 4 shows a magnet suspended on a string and left free to turn. It is marked with an N on the end that points north and an S on the end that points south, and a second magnet is marked in the same manner. By considering the effects of these magnets on one another, some of the basic properties of magnetism can be observed.

To begin the observation, the second magnet is held with the N pole pointing toward the N pole of the magnet hanging on the string, as shown in Figure 4A. If the magnet in the hand is moved toward the magnet on the string, the magnet hanging on the string turns away from the magnet in the hand, as indicated by the arrow.

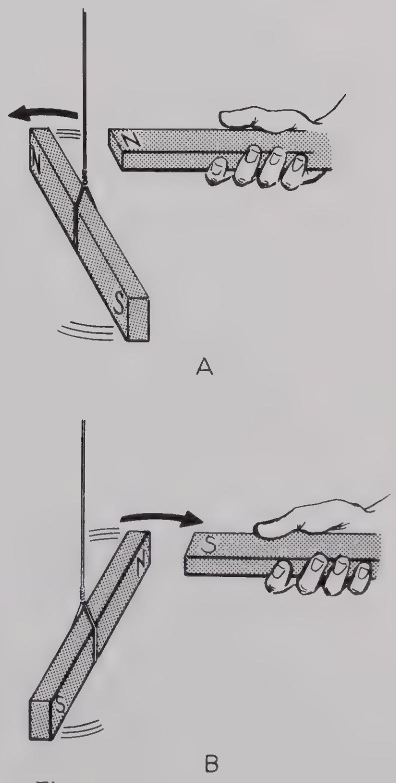
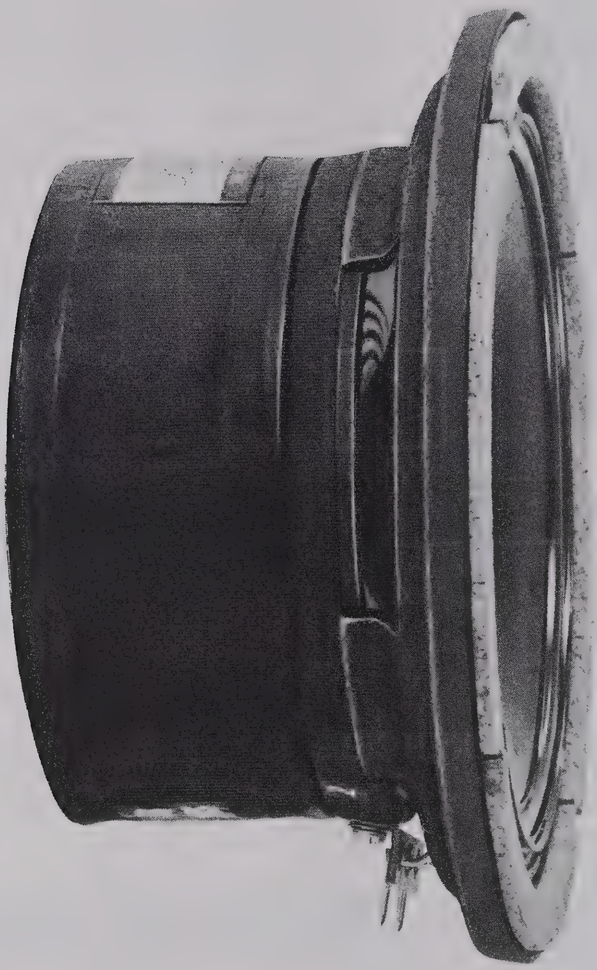


Figure 4

The action is the same as though the held magnet actually was touching and pushing the magnet on the string. However, since the magnets do not touch, it is the invisible force of the magnetic fields causing this action.



A loudspeaker contains both an electromagnet and a permanent magnet. Interaction between the fields produced by the two magnets moves the speaker cone, which, in turn, generates sound waves.
Courtesy T. R. Bozak Mfg. Co.

If the S pole of the held magnet is moved toward the S pole of the magnet on the string, the suspended magnet turns away exactly as it did when the N poles were brought close together.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

MAGNETIC MATERIALS

NATURAL MAGNETS

ARTIFICIAL MAGNETS

MAGNETIC POLES

MAGNETIC FIELDS

1. Only iron (steel), cobalt and nickel are affected by magnetism. True or False?

2. A magnet which holds its magnetism indefinitely is called a ____.

3. Most permanent magnets are made of (a) alnico, (b) soft iron, (c) cobalt.

4. For some applications, we may prefer a temporary magnet. Temporary magnets are made of (a) alnico, (b) soft iron, (c) cobalt.

5. The point of concentration of magnetic force of a magnet is called a ____________________.

6. When held away from other magnets and allowed to move freely, where will the end marked S of a bar magnet point?

7. The area around a magnet which is influenced by the magnet is known as the (a) magnetomotive force, (b) magnetic field, (c) pole.

8. We usually think of the magnetic field as being made up of many magnetic lines of force. The total number of magnetic lines that make up a magnetic field is referred to as the ____________________.

9. The external magnetic lines of force extending between the poles of a magnet are assumed to leave the __________ pole and enter the __________ pole.

10. Magnetic lines of force around a magnet extend only a short distance away from the magnet. True or False?

11. The number of magnetic lines of force passing through a given area is known as the (a) magnetic field, (b) magnetomotive force, (c) magnetic flux, (d) flux density.

12. What is the standard unit of measurement of magnetic flux?

13. What is a tesla?

Next, the held magnet is turned so that the S pole points toward the suspended magnet, as shown in Figure 4B. Again, the held magnet is moved toward the magnet on the string. Now, the N pole of the hanging magnet turns toward the S pole of the held magnet, as indicated by the arrow.

These simple tests demonstrate the two basic laws of magnetism:

LIKE MAGNETIC POLES REPEL
UNLIKE MAGNETIC POLES ATTRACT

The reason for the attracting and repelling action can be shown by using the method of Figure 5A. This time, two magnets are placed in line with their N poles about one inch apart. A piece of glass is then placed over the magnets, and iron filings are sprinkled on the glass.

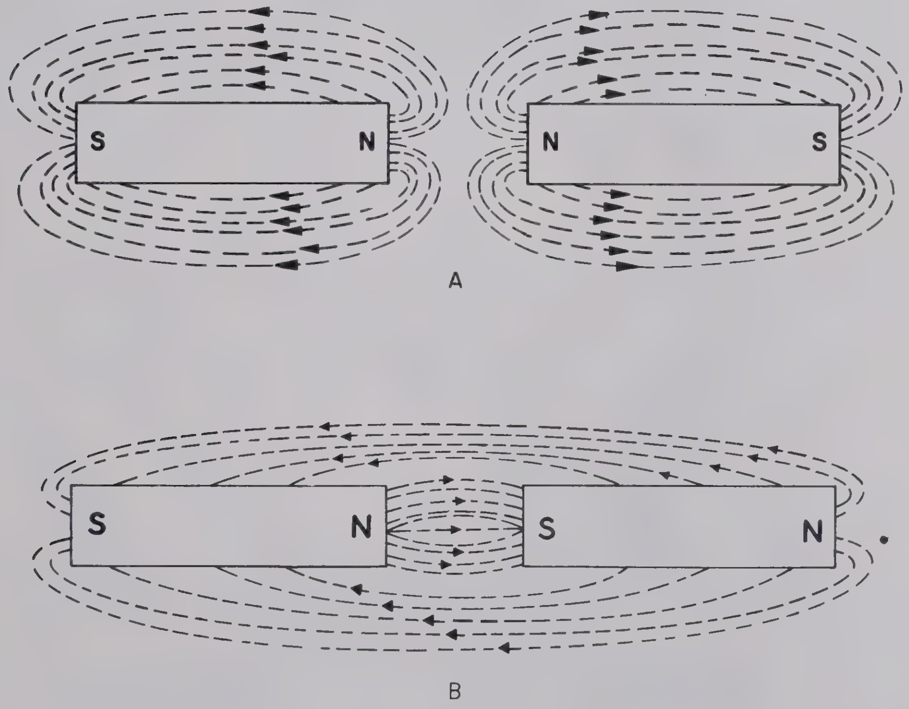


Figure 5

When the glass is tapped gently, the filings arrange themselves in lines which curve away from the end of each magnet, as shown in Figure 5A. By turning one of the magnets around as in Figure 5B and bringing an N and S pole about an inch apart, when the filings again are sprinkled on the glass, they arrange themselves in almost straight lines across the gap between the N and S poles. Think of these magnetic lines as always forming a complete circuit, similar to an electric circuit, except that they pass through every known substance and travel from the N pole, out around to the S pole, and then back through the magnet to the N pole again.

With this in mind, Figure 5A shows that the magnetic lines of each magnet turn around toward their own S pole and have nothing to do with those of the other magnet. In fact, the lines around one magnet seem to crowd those around the other out of the way. On the other hand, in Figure 5B, the lines cross the space from the N pole of one magnet to the S pole of the other, and a single magnetic circuit is completed through both magnets.

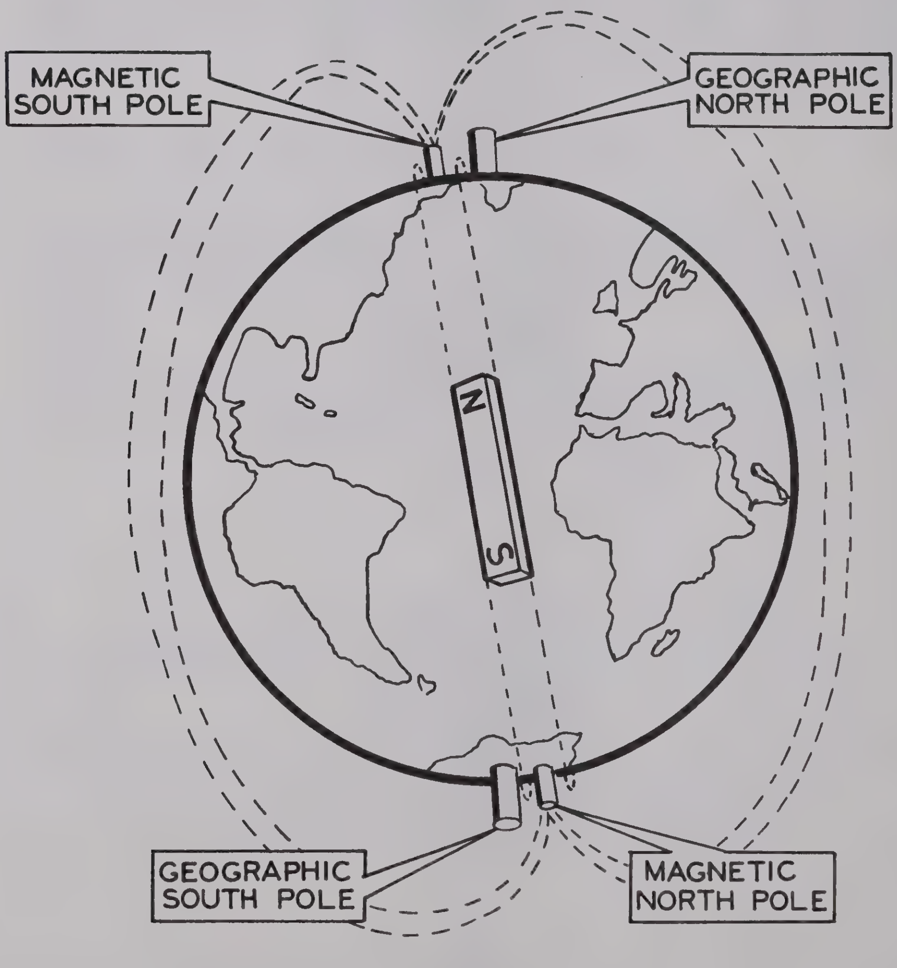


Figure 6

The action of a compass can be explained in a similar manner. The earth is like a huge magnet, producing a magnetic field on the order of that shown in Figure 6. Near the North Geographic Pole of the earth, there is a magnetic pole which is found to attract the north pole of a permanent magnet. There is another magnetic pole near the South Geographic Pole of the earth, and it has been found that this pole attracts the south pole of a permanent magnet. As shown in Figure 6, a magnet that is suspended and allowed to swing freely aligns itself with the magnetic poles of the earth and becomes a part of the earth's magnetic circuit.

Since unlike poles attract, the magnetic pole near the North Geographic Pole must be a south magnetic pole, and the one near the South Geographic Pole must, in reality, be a north magnetic pole. As illustrated in Figure 6, the compass does not point to the true north and south poles of the earth, but rather to the magnetic poles.

The Effect of Distance

In experimenting with magnets, it is found that the magnet has less attracting force on a piece of iron held some distance from the magnet than it does when the same piece of iron is brought closer to the magnet. The amount of pull of a magnet on a piece of iron changes with the number of magnetic lines passing through the iron. Since the lines are concentrated at the poles, the farther from the pole that a piece of iron is moved, the fewer the number of magnetic lines passing through the iron, and therefore, the weaker the pull. This reduction in pull changes quite rapidly, and the reason is illustrated in Figure 7.

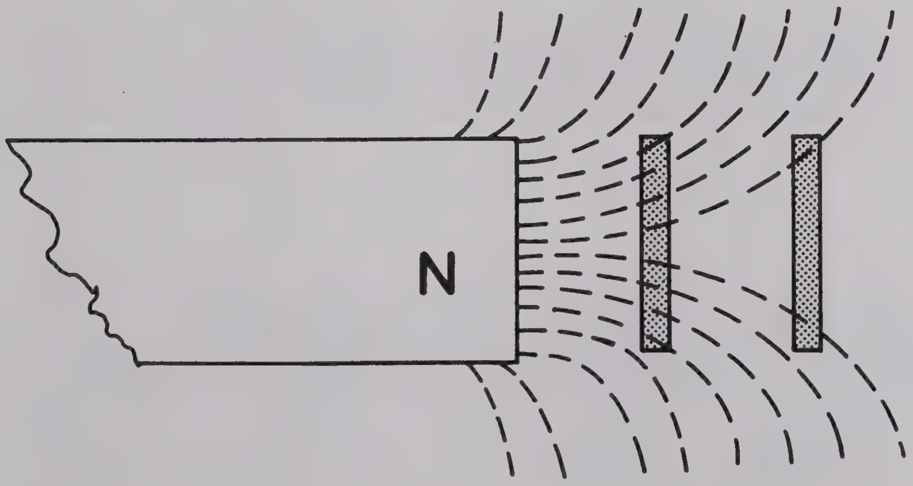


Figure 7

A top view of a bar magnet is shown in Figure 7, and the lines of force which make up the field around this magnet are shown fanning out as they leave the north pole. Just to the right of the pole, the top view of a thin piece of iron is shown, with another piece of iron to the right of this one.

Due to the shape of the magnetic field, there are more lines of force passing through the piece of iron closest to the magnet than through the piece that is farther from the magnet. There are eight lines through the closest piece of iron, and only two lines through the other piece. Although both pieces of iron are made of the same material and have the same dimensions, the one on the right is affected less by the magnet than is the one on the left.

Notice that the piece of iron on the right is twice as far from the magnet, and is affected one-fourth as much as the piece on the left. Stated as a rule for all magnets, the strength varies inversely as the square of the distance between the pole and the object. Thus, an object twice as far from the pole as another object is affected only one-fourth as much, an object three times as far from the pole is affected only one-ninth as much, etc.

MOLECULAR THEORY OF MAGNETISM

If a magnet is broken into pieces, the qualities of magnetism are not lost. As shown in Figure 8, each piece of the original bar magnet becomes an inde-

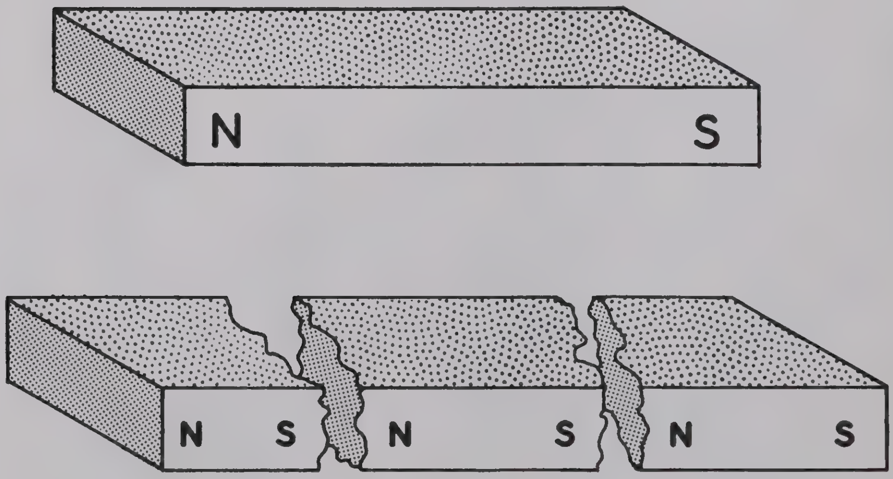


Figure 8

pendent (though weaker) magnet, with an N and S pole of its own. This situation, as well as many other principles of magnetism, can be explained by what is known as the molecular theory. According to this theory, each molecule that goes to make up a material is considered as an extremely small permanent magnet. In iron, steel and some ceramic materials, these molecules are stronger magnets than in any of the other metals.

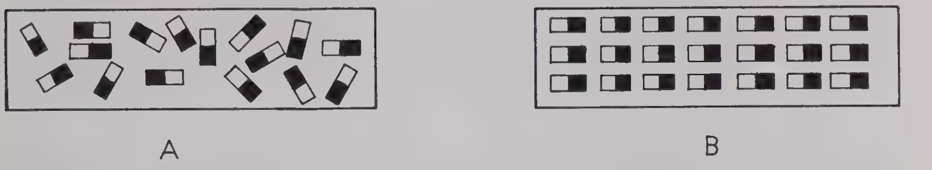


Figure 9

As shown in Figure 9A (the black end represents an N pole and the other end an S pole), the molecules in the ordinary piece of iron or steel are not arranged in any particular order. Since the magnetic influences are exerted in practically all directions, the magnetic fields cancel out within the metal. However, since unlike poles attract each other, when the iron or steel is put in a strong magnetic field, the molecules turn in one direction, as in Figure 9B. The individual magnetic fields combine to make the entire piece of metal act as one large magnet, with the N pole on the right and the S pole on the left.

Magnetic Induction

As mentioned earlier in the lesson, certain materials can be magnetized while under the influence of a magnetic field, but lose their magnetism as soon as the field is removed. Materials of this type are temporary magnets, and one of the materials most commonly used in temporary magnets is soft iron.

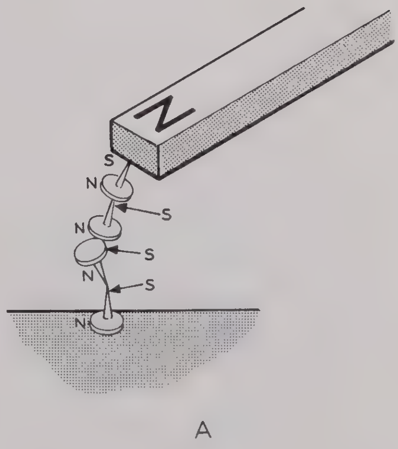


Figure 10

As illustrated in Figure 10A, ordinary tacks can become temporary magnets if they are brought under the influence of a magnetic field. A tack is placed on the end of a permanent magnet and itself becomes a small magnet. A south pole is set up at the end of the tack that touches the north pole of the permanent magnet, and the opposite end of the tack becomes a north pole.

If another tack is brought in contact with the one suspended from the permanent magnet, this second tack also becomes a temporary magnet with

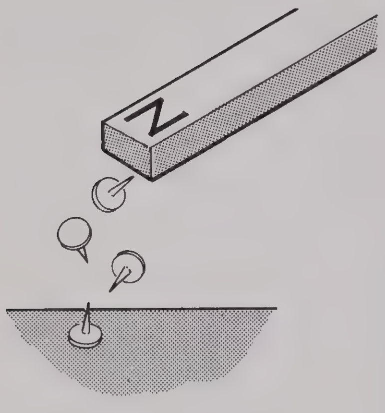


Figure 10

its own north and south poles. A third tack, brought in contact with the second one, becomes another temporary magnet. In fact, if the original magnet is strong enough, a long string of tacks can be formed in this manner.

This process of setting up magnetism in an object that is under the influence of a magnetic field is called **MAGNETIC INDUCTION**. If the original magnet is taken away from the first tack, the magnetic poles at the ends of the tacks disappear, and there is no longer a force to hold them together. As shown in Figure 10B, the entire string of tacks falls apart instantly.

The reason for magnetic induction is best explained by the molecular theory. The molecules that make up the tack material are turned very easily from the random state of Figure 9A to the state of alignment illustrated in Figure 9B. However, these molecules turn back to their original state just as easily when the original magnet is removed. This characteristic distinguishes temporary magnets from permanent magnets. In a material such as hardened steel, the molecules require a great deal of magnetic force to bring them into magnetic alignment, but once this alignment occurs, the steel tends to maintain its magnetism indefinitely.

Reluctance and Permeability

Because most of the molecules of soft iron turn quite easily under the influence of a magnetizing force, the overall magnetic effect is quite strong. In some other materials, very few or none of the molecules turn because of the rigid structure of the material. In other materials, the magnetic field for each molecule is quite small. In either of the last two cases, the total magnetic effect is very weak.

Although magnetic lines of force pass through all substances under normal conditions, some materials do not carry them as readily as others. This opposition which a substance offers to the passage of magnetic lines is known as its **RELUCTANCE.**

Reluctance is a property of every material. Just as there is no perfect electric conductor, under normal conditions, there is no perfect magnetic conductor. However, soft iron has a very low reluctance and is a good conductor of magnetic lines in comparison with most other materials. Reluctance describes the opposition offered to magnetic lines of force. The term **PERMEABILITY** describes the ease of passage of magnetic lines of force. Thus, a material with a high permeability has a low reluctance, and vice versa.

Measurements of permeability are taken with air as the reference. Air has a permeability of one. Iron, for example, has a permeability several thousand times that of air. The Greek letter μ (mu) is often used to represent permeability.

MAGNETIC CIRCUITS

The paths taken by magnetic lines of force can be thought of in much the same way as the current paths in an electric circuit. In an electric circuit, pressure or voltage overcomes the resistance of the conducting path and sets up a current. In a magnetic circuit, similar conditions exist, but instead of voltage or electromotive force (emf), there is a MAGNETOMOTIVE FORCE (mmf) which causes magnetic lines throughout the circuit.

The opposition which the magnetic circuit offers to this flux is known as reluctance. Electrically, nearly all materials have different resistance characteristics, some offering little and others offering high opposition to an electric current. However, with the exception of the magnetic metals, most substances offer nearly equal reluctance. Air and some other nonmagnetic materials have high reluctance.

To further compare the magnetic circuit with an electric circuit: there is an mmf instead of voltage; line of force, or flux lines, instead of current; and reluctance instead of resistance. The relationship between mmf, flux and reluctance in the magnetic circuit is very similar to the relationship between voltage, current and resistance in the electric circuit. Just as current is equal to voltage divided by resistance, flux is equal to magnetomotive force divided by reluctance.

MAGNETIC SHIELDING

So far as anyone knows, magnetic lines pass through all materials at normal temperatures. In illustrating the magnetic fields through the use of iron filings, the magnet is placed under a piece of glass, and iron filings are sprinkled on top of the glass. Even though glass is a poor conductor of magnetic lines, the glass is unable to insulate the iron filings from the effects of the magnetic field.

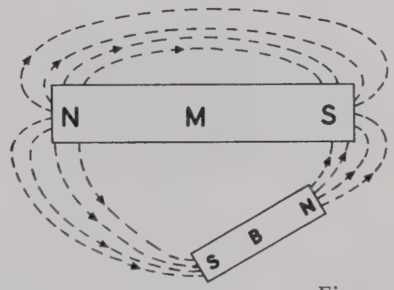


Figure 11

In Figure 11, when a bar of soft iron, B, is placed in the field of a permanent magnet, M, magnetic induction causes the iron to become a temporary magnet having an N and S pole, as explained for Figure 10. Soft iron offers less reluctance than the surrounding air to the passage of magnetic lines, and the lines of force leaving the N pole of the permanent magnet take the path of least reluctance through the iron back to the S pole of the permanent magnet. Thus, the magnetic field is pulled out of its natural shape by the piece of iron.

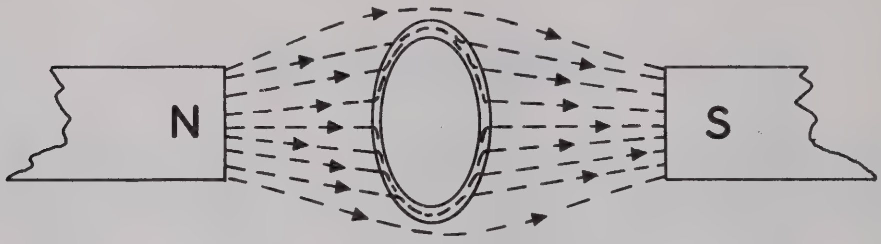


Figure 12

This ability of a magnetic material to distort the field can be used to good advantage when it is necessary to shield some object from the effects of a magnet. It may seem strange to use a good conductor of magnetic lines as a means of insulation, but the reason is that the magnetic substance carries the magnetic lines so much easier than air or other materials that, instead of passing through the object to be shielded, the field is distorted and passes around the object through the magnetic material. This arrangement is called a **MAGNETIC SHIELD** and, as indicated in Figure 12, the magnetic lines do not pass through the space inside the shield.

This method often is used in shielding watches against the effects of magnetism. The case of the watch is made of a magnetic material, and lines of force pass through the case, around the mechanism. This prevents the mechanism from being unbalanced or thrown out of timing by the magnetic field in which it is placed.

ELECTROMAGNETISM

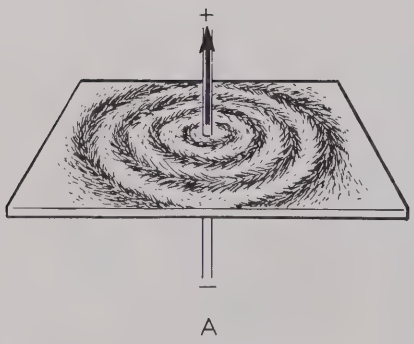


Figure 13

It has been found that an electric current sets up a magnetic field similar to that produced by a permanent magnet. This action is known as **ELECTROMAGNETISM** and is very important in many devices. A desirable feature of electromagnetism is that it is possible to control the strength and polarity of the magnetic field.

In order to demonstrate the existence and properties of a magnetic field produced by an electric current, the experiment shown in Figure 13A is used.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

ATTRACTION AND REPULSION

THE EFFECT OF DISTANCE

MOLECULAR THEORY OF MAGNETISM

MAGNETIC INDUCTION

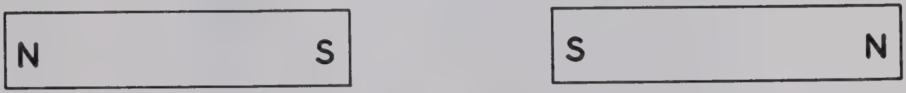
RELUCTANCE AND PERMEABILITY

MAGNETIC CIRCUITS

MAGNETIC SHIELDING

14. The south pole of a compass points toward the earth's South Geographic Pole. This proves that what we call the earth's South Geographic Pole is actually a north magnetic pole. True or False?

15. In the diagram below, draw the lines of force to show why like poles repel.



16. The effect of a magnet on a piece of iron varies directly as the square of the distance between the magnet and the iron. True or False?

17. When an object is magnetized due to its PRESENCE in a magnetic field, we call the process (a) magnetism, (b) magnetic induction, (c) reluctance, (d) magnetomotive force.

18. The individual molecules of iron are tiny permanent magnets. When placed in a strong magnetic field, these tiny magnets tend to line up in the same direction so that their magnetic fields aid each other. True or False?

19. The opposition of a material to magnetic lines of force is known as its ______________________.

20. **Soft iron has zero reluctance, whereas aluminum has infinite reluctance. True or False?**

21. **Material with a low reluctance also has a high permeability. True or False?**

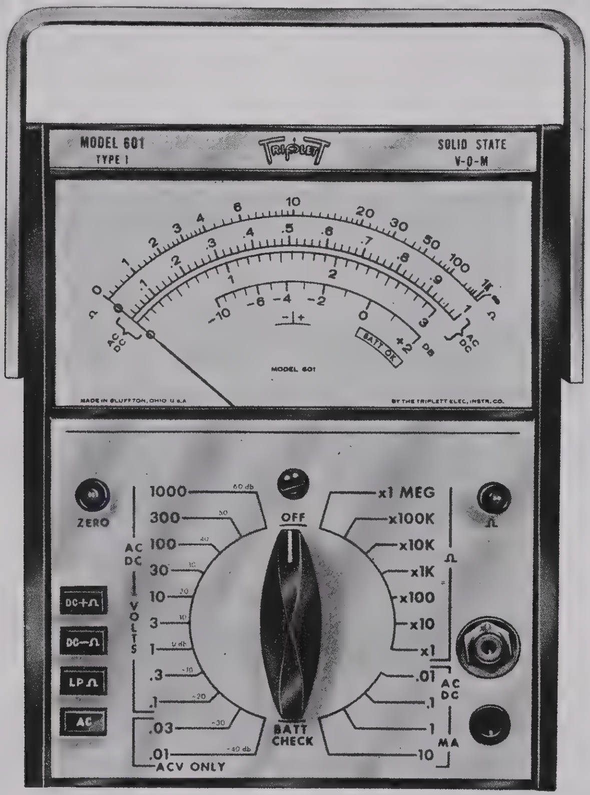
22. **Magnetomotive force (mmf) in a magnetic circuit may be compared to (a) voltage in an electric circuit, (b) current in an electric circuit, (c) resistance in an electric circuit.**

23. **Flux in a magnetic circuit is comparable to ______________ in an electric circuit.**

24. **The reluctance of air is one, as a reference. True or False?**

25. **We can shield an object from the effects of a magnetic field by surrounding it with a material which has a high reluctance to magnetic lines of force. True or False?**

A wire is inserted through a piece of cardboard and connected to a voltage source. Electrons flow from negative to positive in the wire, as shown by the vertical arrow. Iron filings, sprinkled on the cardboard, form a noticeable pattern of rings around the wire. This pattern shows that a circular magnetic field is set up around the current-carrying wire.



The pointer in the meter above is attached to an electromagnet. Current in the electromagnet develops a magnetic field which interacts with the field from a permanent magnet. The result is a movement of the pointer in accordance with the current through the coil.
Courtesy The Tripplett Electrical Instrument Co.

If the iron filings are removed and a magnetic compass is placed on the cardboard, the nature of the magnetic field can be demonstrated further. In Figure 13B, a compass is moved from point to point in a circle around the cardboard, and the effect on the position of the compass needle is noted. The compass needle no longer points north and south. It changes direction continuously as the compass is moved about the wire. Since the compass needle normally aligns itself with the magnetic field of the earth, there must be another field, other than the earth's field, which deflects the pointer in this manner.

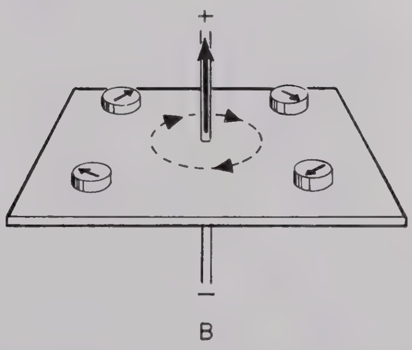


Figure 13

When there is no current in the wire, the compass points north and south, regardless of its position on the cardboard. Therefore, it is the current and not the wire that produces the magnetic field.

Similar to the effects of distance in a permanent magnet, the magnetic field intensity is greatest near the wire. It decreases as the distance between the wire and the compass is increased.

In the two basic laws of magnetism, if the magnetized needle of the compass is placed in a magnetic field, its N pole turns away from another N pole while its S pole is attracted toward the other N pole. Similarly, the N pole of the compass is attracted to, and the S pole is repelled by, the S pole of the other magnet. The result is a double action: a pull on one end, and a push on the other. This double action causes the compass needle to line up with the magnetic field in which it is placed.

When moved around the wire, as shown in Figure 13B, the changing positions of the compass needle trace a circle. Therefore, we have further proof that the magnetic field around the wire is circular in shape.

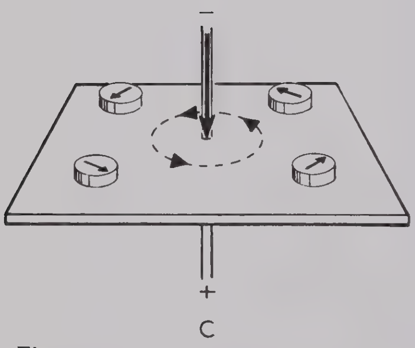


Figure 13

To continue this investigation of the electromagnetic action, the connections of the wire are reversed so that the electrons pass down through the wire as shown in Figure 13C. When the compass is moved around the wire, the changes of needle position still trace a circle. However, the needle now points in the opposite direction to that shown in Figure 13B. Thus, a reversal of current direction through the wire causes a reversal in the direction of the magnetic field.

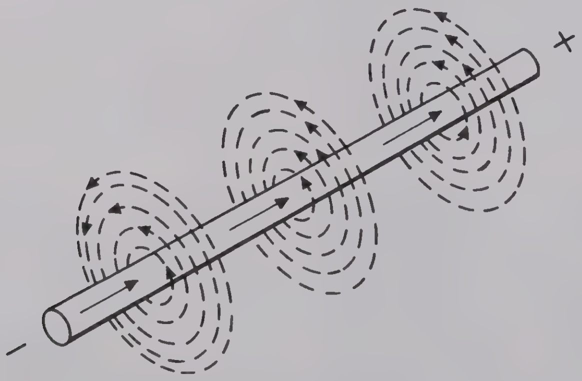


Figure 14

Raising or lowering the cardboard along the wire has no effect on the action of the compass, and it continues to trace a circle as it is moved around the wire. Thus, the magnetic field around a straight wire exists uniformly along the wire, as illustrated in Figure 14. At any point along the wire, a similar magnetic field is present.

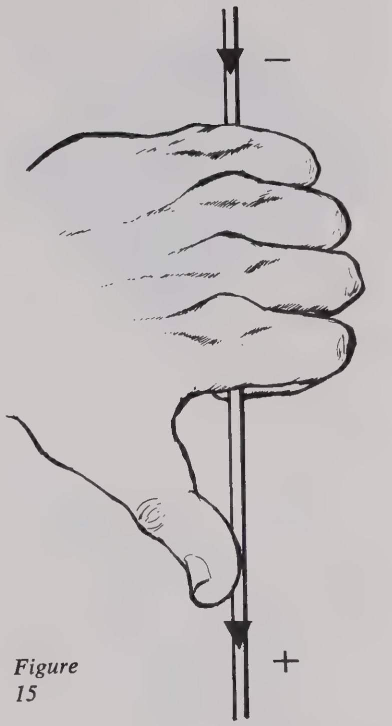


Figure 15

Left Hand Current Rule

The above actions show that there is a definite relationship between the direction of electron flow and the direction of the magnetic field it produces. It so happens that the thumb and fingers of the left hand can be used as a convenient means of determining this relationship. For example, as shown in Figure 15,

BY HOLDING THE WIRE IN THE LEFT HAND, WITH THE THUMB POINTING IN THE DIRECTION OF THE ELECTRON FLOW, THE FINGERS SURROUND THE WIRE IN THE SAME DIRECTION AS THE MAGNETIC FLUX.

This is called the **LEFT HAND CURRENT RULE.**

This simple rule is very useful because, if the direction of the electron flow is known, the direction of the magnetic field can be found. The rule can also be used in reverse; that is, if the direction of the magnetic field is known, the direction of the electron flow can be determined.

MAGNETIC FIELD AROUND A COIL

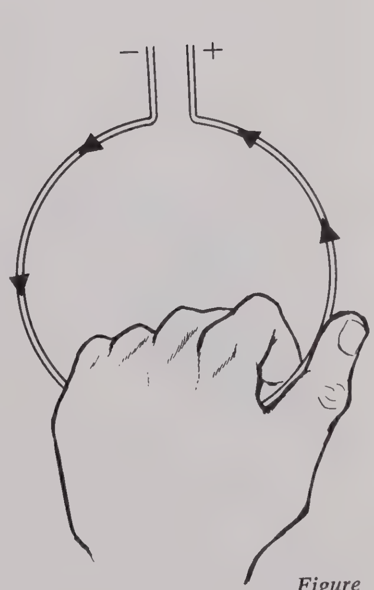


Figure 16

In Figure 16, a length of wire is bent to form a loop. Using the Left Hand Current Rule, when the electron flow is in the direction shown by the arrows, the fingers point around toward the inside of the loop no matter on which part of the wire the hand is placed.

To investigate further, the wire is bent into several loops, or a "coil," as in Figure 17A. Each loop of the coil passes through a hole in a piece of cardboard, so that the coil itself is formed right on the cardboard. Then, iron filings are sprinkled on the cardboard to demonstrate the magnetic action.

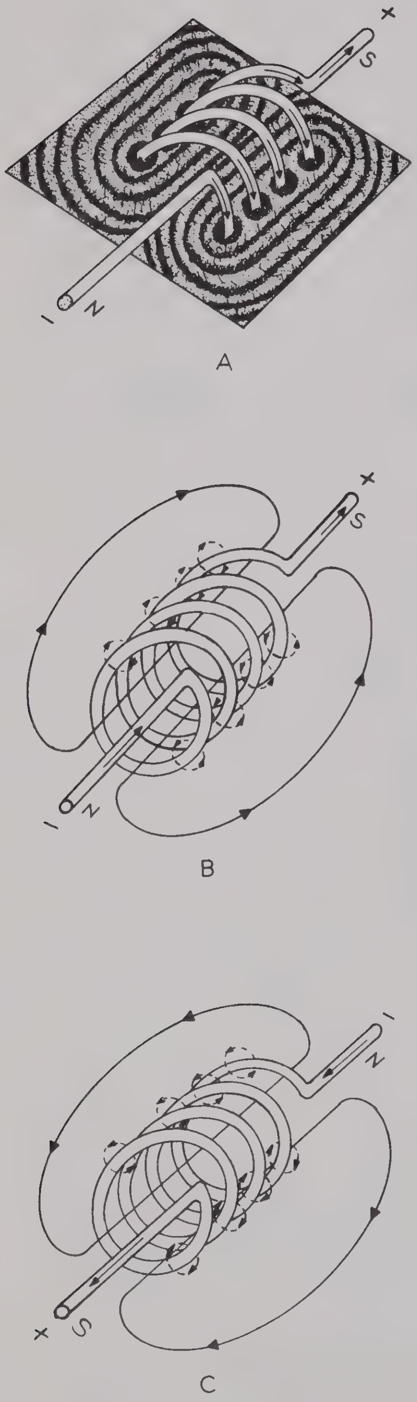


Figure 17

When current is passed through the coil, in the direction of the arrows, the filings align themselves in a definite pattern on the cardboard.

As shown in Figure 17A, there is a circular magnetic field around each loop at the point where the loop passes through the cardboard. These fields are exactly the same as the one illustrated in Figure 13A. However, each of these fields combines with the ones that are next to it, and a single field is formed around the entire length of the coil. Notice the similarity between the pattern formed around the coil on the cardboard and the one formed around the permanent magnet of Figure 3A.

The structure of the field around the coil is shown in the simplified sketch of Figure 17B. The small, circular fields around each loop are represented by the small dashed, arrowed lines, and the field around the entire coil is shown by the solid, arrowed lines. The arrows within the conductor show the direction of electron flow through the coil.

Due to the direction of the lines of force which make up the overall field, the lower left end of the coil becomes a north magnetic pole and the upper right end a south magnetic pole. The flux lines extend from the N pole to the S pole outside the coil, and from the S pole to the N pole inside the coil. The current-carrying coil presents the same magnetic characteristics as the permanent magnets described earlier in the lesson.

If the direction of electron flow reverses, the direction of the magnetic field also reverses. In Figure 17C, the effect of reversing the current direction is illustrated. As shown by the arrows within the conductor, the electrons move through the loops in the opposite direction to that of Figure 17B. As a result, the small circular fields represented by the dashed, arrowed lines are reversed, and the overall field shown by the solid, arrowed lines is reversed also. The upper right end of the coil now becomes an N pole and the lower left end, the S pole.

Left Hand Coil Rule

The relationship between the direction of electron flow and the polarity of the resultant field is indicated by what we call the **LEFT HAND COIL RULE.** As shown in Figure 18,

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WITH THE FINGERS POINTING AROUND A COIL IN THE DIRECTION OF THE ELECTRON FLOW, THE THUMB POINTS TOWARD THE N POLE OF THE MAGNETIC FIELD.

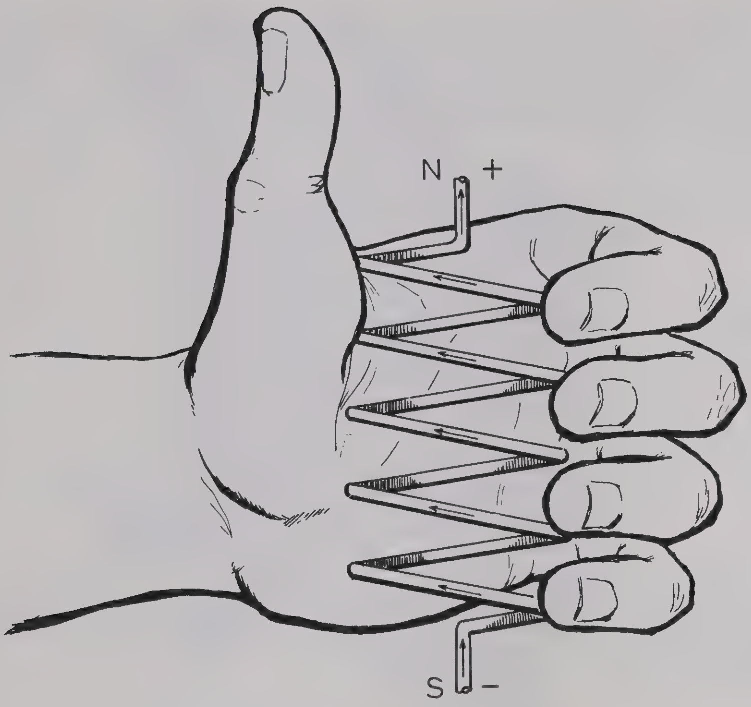


Figure 18

When current exists in a coil similar to the one shown in Figure 18, the coil has all the magnetic qualities of a permanent magnet and is called an **ELECTROMAGNET**. If this electromagnet is brought near a permanent magnet or another electromagnet, the like and unlike poles react exactly as explained for the permanent magnets. Moreover, an increase of current in the coil increases the strength of the magnetic field, and a decrease of current weakens the field.

Ampere-Turns

When the number of loops or turns of the coil is increased and the current remains the same, the strength of the magnetic field increases. Each loop or turn of the coil sets up its own magnetic field, which unites with the fields of other loops to produce the field around the entire coil. The more loops, the more magnetic fields unite and reinforce each other and, as a result, the total magnetic field becomes stronger.

To compare the magnetic strength of different coils, and to obtain a basis for measuring the magnetomotive force of an electromagnet, the number of turns of wire is multiplied by the number of amperes of current carried by the wire and the result is called **AMPERE-TURNS (NI)**. The ampere-turn is the unit for measuring the magnetomotive force of a current-carrying coil. In a formula, the magnetomotive force in ampere-turns can be expressed as:

$$F = NI \qquad (2)$$

where: F = magnetomotive force in ampere-turns,

N = number of turns, and

I = current in amperes.

For example, a coil with 10 turns and a current of 10 amperes has an F of 100 ampere-turns. Another coil with 50 turns and a current of 2 amperes also has an F of 100 ampere-turns.

Effect of an Iron Core

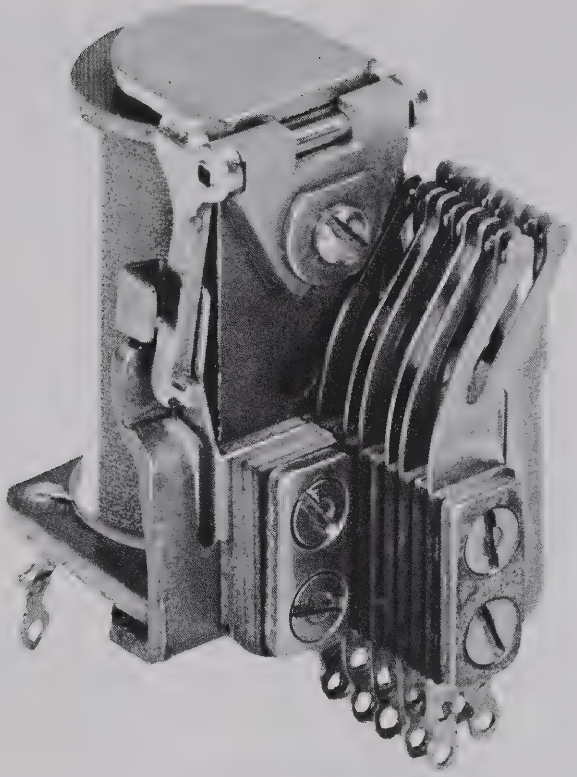
Earlier in this lesson, it was stated that iron and steel have low reluctance and carry magnetic lines of force much more readily than air and certain other materials. To increase the magnetic field of a coil, it is common practice to insert a piece of iron through the center of the coil. The iron is called the **CORE**, and its low reluctance permits passage of many more magnetic lines of force through it than the surrounding air will carry. It tends to concentrate the coil's magnetic field.

The magnetic behavior of a coil carrying an electric current can be summed up in the following three statements:

Whenever current is present in a coil of wire, a magnetic field is set up in and around the coil, which then exhibits all of the properties of a magnet.

The strength of the magnetic field varies with the number of turns and the current. With no current, there is no magnetism.

An iron core, placed inside the coil, permits a large increase in the strength of the magnetic field by providing a magnetic circuit with less reluctance than air.



The relay shown above is an electromagnet with an iron core. When the coil is energized, the resultant magnetic field pulls the armature towards the core, actuating the relay contacts.

Courtesy Automatic Electric Co.

USES OF ELECTROMAGNETS

When it is desired to produce mechanical motion by electricity, usually some form of electromagnet is used. In almost every instance, the part to be moved is made of magnetic material, which is placed quite close to the electromagnet.

The doorbell is a good example of the use of an electromagnet to produce mechanical motion. In Figure 19, a bell of this kind is shown with the cover removed to expose the main parts. Starting at the top is the "gong," or bell, while directly below it is the armature, which has a small ball, or "hammer," attached to its upper end.

The coil of wire for the electromagnet is wound on a cylindrical iron core, riveted to the center of a U-shaped iron frame which is mounted on the main base of the doorbell. The armature extends across the open end of the U of this frame and is held in position by the spring, which is riveted to both the armature and the frame.

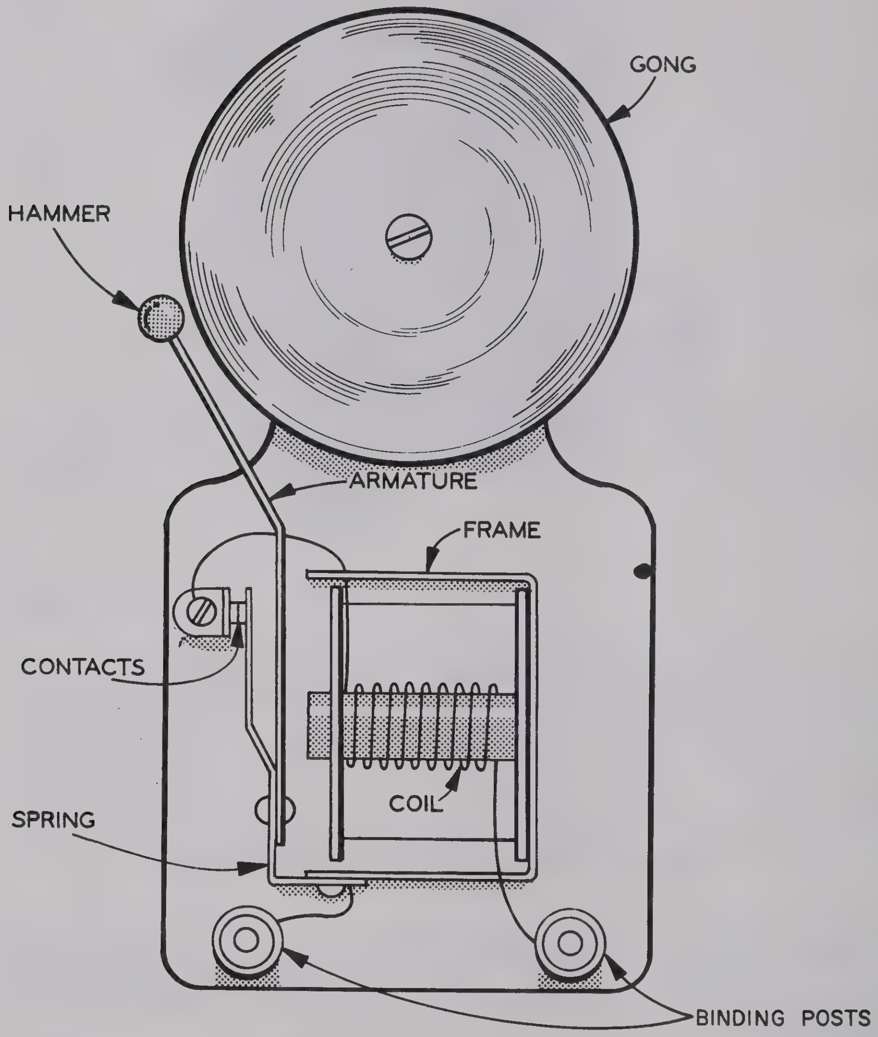


Figure 19

The upper end of the spring is bent away from the armature and carries a contact which is in line with another contact mounted on, but electrically insulated from, the main base. The spring tension tends to pull the armature away from the frame and to hold the contacts together, as shown in Figure 19.

There is an electric circuit from the right hand binding post, up through the turns of the coil and over to the stationary contact. As the spring holds the contacts together, the circuit continues through the spring to the left hand binding post. To simplify the drawing, only a few turns of wire are shown in the coil, but actually several hundred turns are employed to fill the entire spool. The large number of turns provides a greater number of ampere-turns at low current, and thus provides a more satisfactory operating condition.

To use the bell, it is connected in an electric circuit which contains a source of voltage and a push-button switch. When this circuit is closed by the switch, current is carried by the coil, and a magnetic field is set up across the open end of the U-shaped magnet frame.

Since the iron armature is located in this field, the armature is attracted toward the frame as soon as the magnetic pull is strong enough to overcome the tension of the spring. When this happens, the armature moves toward the coil from the position shown in Figure 19.

The movement of the armature does two things: First, the ball on the upper end strikes the gong and causes the bell to ring; second, the contact on the upper end of the spring no longer touches the stationary contact and, consequently, the circuit is opened. As soon as the circuit is opened, the current is interrupted, the magnetic field dies out, and the spring pulls the armature back to the position of Figure 19. The instant the contacts touch, the circuit is completed, there is current through the coil and the entire action is repeated.

The movement of the armature is quite rapid, and as long as the push-button switch is held closed, the armature vibrates with the hammer on its upper end striking the gong each time the magnet pulls it over. While the doorbell is a simple example, it illustrates one common method by which the electric current in a coil is converted to magnetic energy that attracts an armature and causes mechanical motion.

Instead of converting electric power to motion, a magnetic field can be used to convert mechanical motion to an alternating voltage or alternating current. Using this principle, ac voltages are generated for use in your home as well as equipment used in electronics. A device commonly called a generator performs this action, and its operation is described in the next lesson.

SUMMARY

The basic principles of magnetism and electromagnetism have been outlined in this lesson. It was found that magnetic deposits are located at certain places on the earth, and that it is possible to induce magnetism in certain other materials by bringing them under the influence of these natural magnets. In general, materials that accept magnetism are called magnetic (or ferromagnetic, if they are made from iron), while materials that are not appreciably affected by magnetism are called nonmagnetic.

The materials that are affected by magnetism, but lose their magnetism as soon as the source is removed, are called temporary magnets. Materials that hold their magnetism after the source has been removed are called permanent magnets. Soft iron is a typical temporary magnet substance, while hard steel is an example of a permanent magnet substance. Some ceramics and alloys of aluminum, nickel and cobalt often are used as magnetic materials because of the special properties they possess.

In a magnet, the points at which the magnetism is concentrated are called its poles. Every magnet has a north and south pole. The fundamental laws of magnetism state that **like** magnetic poles repel each other, while **unlike** poles attract each other. The area around the magnet is termed a magnetic field. The field consists of imaginary lines which are considered to extend from the north pole to the south pole outside the magnet, and from the south pole to the north pole inside the magnet. The term, magnetic flux, is given to all the lines of force making up the magnetic field.

The opposition to magnetic flux is known as reluctance, which corresponds to resistance in an electric circuit. There is a definite relationship between the flux, the magnetizing force and the reluctance. This relationship corresponds to Ohm's Law for electric circuits. According to the magnetic relationship, the flux is directly proportional to the magnetizing force, and inversely proportional to the reluctance.

Magnetism can be produced by passing an electric current through a conductor. The resulting field around the conductor is assumed to consist of circular magnetic lines, or a series of magnetic rings. If the conductor is formed into a number of loops or turns to produce a coil, the circular field around each turn combines with that of the other turns to form a single field extending from one end of the coil to the other. With a pole formed at each

The following Practice Exercise questions cover the subjects which you have just studied. They are:

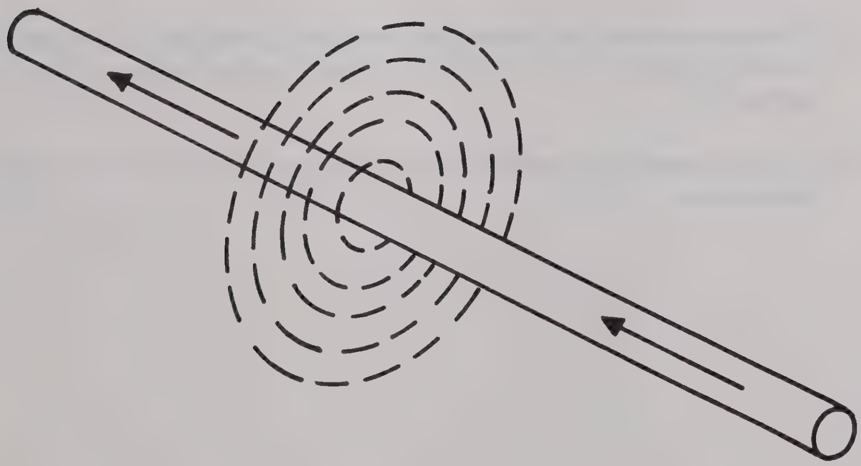
- ELECTROMAGNETISM
  - LEFT HAND CURRENT RULE
- MAGNETIC FIELD AROUND A COIL
  - LEFT HAND COIL RULE
  - AMPERE-TURNS
  - EFFECT OF AN IRON CORE
- USES OF ELECTROMAGNETS

26. The process or action of producing a magnetic field by passing an electric current through a conductor is known as ____________________.

27. The shape of the magnetic field surrounding a conductor through which there is current is a pattern of ____________.

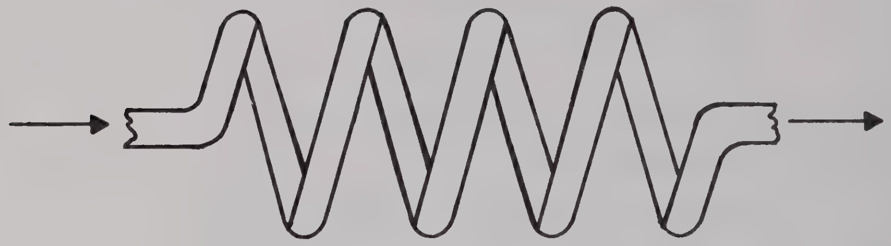
28. What is the effect on the magnetic field around a conductor when the direction of current through the conductor is reversed?

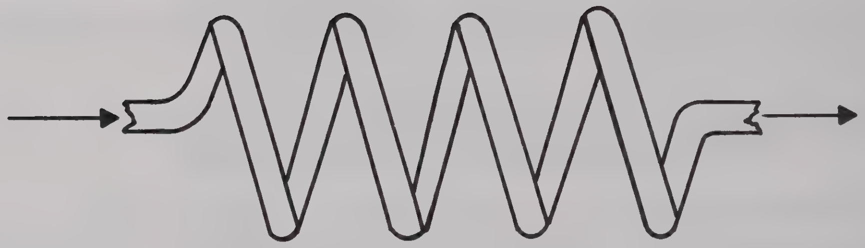
29. Shown below is a wire with current in the direction shown by the arrows. Use the Left Hand Current Rule to determine the direction of magnetic flux around the wire and draw arrowheads on the dashed lines to indicate this direction.



30. If a current-carrying conductor is formed into a series of loops, the magnetic field of each loop tends to ____________________ the field of a nearby loop.

31. Shown below are two coils with current in the direction shown by the arrows. Using the Left Hand Coil Rule, show the polarity of the poles at the ends of each coil. (Hint—draw current arrows on each loop.)





32. What is the unit for measuring the magnetomotive force of a current-carrying coil?

33. Without increasing the current flow through a given coil or the number of turns of the coil, how can the strength of the magnetic field be increased?

34. In the example of a doorbell, the moving part is the (a) coil, (b) frame, (c) armature.

end of the coil, the direction of the field is from the north pole to the south pole outside the coil, and from the south pole to the north pole inside the coil. This field has all the qualities of that produced by a regular magnet.

Certain rules are applied to determine the direction of the magnetic field when the direction of current is known. The Left Hand Current Rule permits us to find the direction of the field around a straight conductor, while the Left Hand Coil Rule is used to determine the direction of the field around a coil. These two rules also can be used in reverse to find the direction of electron flow when the direction of the field is known.

An important feature of the electromagnet is that the strength and direction of its field can be controlled. By reversing the direction of the current through a coil, the polarity of the magnetic field is reversed. The strength of the field is changed by varying the amount of current through the coil. This control action is put to use in many ways in the operation of electronic circuits.

IMPORTANT DEFINITIONS

ALNICO — A group of alloys of iron, aluminum, nickel and cobalt, used extensively in artificial permanent magnets.

AMPERE-TURNS (NI) — Units of the magnetomotive force produced by a current-carrying coil. One ampere-turn represents the mmf produced by a current of one ampere through one turn of wire. The previously used unit of magnetomotive force was the GILBERT, which is equal to 0.796 ampere turn.

ARTIFICIAL MAGNET — A magnet formed by placing a magnetic material in a magnetic field.

CORE — A piece of magnetic material inserted through the center of a coil to provide a low-reluctance path for the magnetic lines of force.

ELECTROMAGNET — A coil of wire exhibiting magnetic properties when it carries a current.

ELECTROMAGNETISM — Magnetism produced by a current-carrying coil.

FLUX DENSITY — The number of lines of force passing through a given area.

LEFT HAND COIL RULE — A method of determining either the polarity of the magnetic field of a coil or the direction of electron flow through the coil, if one of these is known: when the fingers of the left hand curve around the coil in the direction of electron flow, the thumb points toward the north pole of the magnetic field.

LEFT HAND CURRENT RULE — A method of determining the direction of electron flow or the direction of the magnetic field for a conductor, if one of these is known: when the thumb of the left hand points along a wire in the direction of electron flow, the fingers will surround the wire in the same direction as the magnetic flux.

MAGNET — An object exhibiting the property of magnetism.

MAGNETIC FIELD — The space around a magnet in which the effect of the magnet can be noticed.

MAGNETIC FLUX — All of the magnetic lines of force that go to make up a magnetic field.

IMPORTANT DEFINITIONS (Continued)

MAGNETIC INDUCTION — The process of setting up magnetism in an object that is placed in a magnetic field.

MAGNETIC LINES — The imaginary lines of force that make up a magnetic field.

MAGNETIC POLE — The point at which the magnetic lines are concentrated. In every magnet, there is one north pole and one south pole.

MAGNETIC SHIELD — A piece of magnetic material used to carry the magnetic lines around an object to prevent the object from being affected by the magnetic field.

MAGNETISM — The property of certain materials to attract iron and other magnetic materials.

MAGNETITE — A certain type of ore which, in its natural state, has the property of magnetism.

MAGNETOMOTIVE FORCE (mmf) — The force that sets up a magnetic field within and around an object.

NATURAL MAGNET — A material which, in its natural state, possesses the qualities of a magnet. Magnetite is a natural magnet.

PERMEABILITY (μ) — A measure of how easily magnetic lines of force can pass through a material.

PERMANENT MAGNET — An artificial magnet that retains its magnetism after the magnetizing force has been removed. Steel, when properly processed, can be made into a permanent magnet.

RELUCTANCE — The opposition of a material to magnetic lines of force. Reluctance in the magnetic circuit corresponds to resistance in the electric circuit.

TEMPORARY MAGNET — An artificial magnet that loses its magnetism soon after the magnetizing force is removed. Soft iron is an example of a temporary magnet.

TESLA — Standard unit of magnetic flux density equal to one weber per square meter. The previously used unit of flux density was the GAUSS, which was equal to one magnetic line per square centimeter.

WEBER (Wb) — Standard unit of magnetic flux measurement equal to 100,000,000 or 10^8 lines of force. The previously used unit of magnetic flux was the MAXWELL, which was equal to one magnetic line of force.

ESSENTIAL SYMBOLS AND EQUATIONS

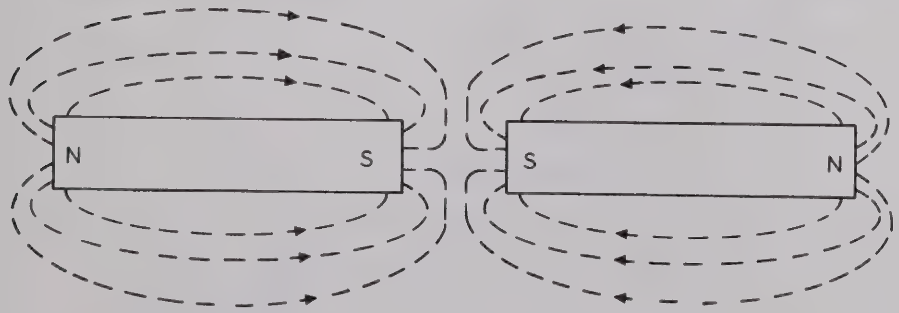
B	Flux density in teslas
F	Magnetomotive force in ampere-turns
I	Current in amperes
m^2	The cross-sectional area of the magnetic path in square meters (one meter equals 3.28 ft.)
N	Number of turns
ϕ	Number of lines of force in webers

$$B = \frac{\phi}{m^2} \tag{1}$$

$$F = NI \tag{2}$$

PRACTICE EXERCISE SOLUTIONS

1. False — All materials are affected to some extent by magnetism.
2. permanent magnet
3. (a) alnico. — Although a permanent magnet may be made of steel, the alnico alloys are more popular for magnets because they hold the magnetism longer. Ceramic magnets are less widely used than alnico magnets.
4. (b) soft iron.
5. magnetic pole — Often, we just call it a pole.
6. The S end (south pole) of a bar magnet will point toward the earth's south geographic pole.
7. (b) magnetic field.
8. magnetic flux
9. north; south — Through the magnet itself, lines travel from the south pole to the north pole.
10. False — Magnetic lines actually extend indefinitely into space around a magnet, but as they spread out and become farther apart, the magnetic effect weakens.
11. (d) flux density.
12. The weber is the standard unit of flux measurement.
13. The tesla is the standard unit of flux density and is equal to one weber per square meter.
14. True — Like magnetic poles repel and unlike magnetic poles attract. The south pole of a compass magnet will point only toward a north pole of any other magnet.
15.



16. False — The strength of the magnetic field varies inversely as the square of the distance from the magnet.

PRACTICE EXERCISE SOLUTIONS (Continued)

17. (b) magnetic induction.

18. True — This is why an unmagnetized piece of iron becomes a magnet when placed in a magnetic field.

19. reluctance

20. False — At normal temperatures, there is no perfect magnetic conductor with zero reluctance, nor is there a perfect magnetic insulator with infinite reluctance.

21. True — Reluctance and permeability are opposite qualities. When one is high, the other is low.

22. (a) voltage in an electric circuit. — Flux lines may be compared to current, and reluctance compared to resistance.

23. current

24. False — Permeability uses air as a reference, with a value of one.

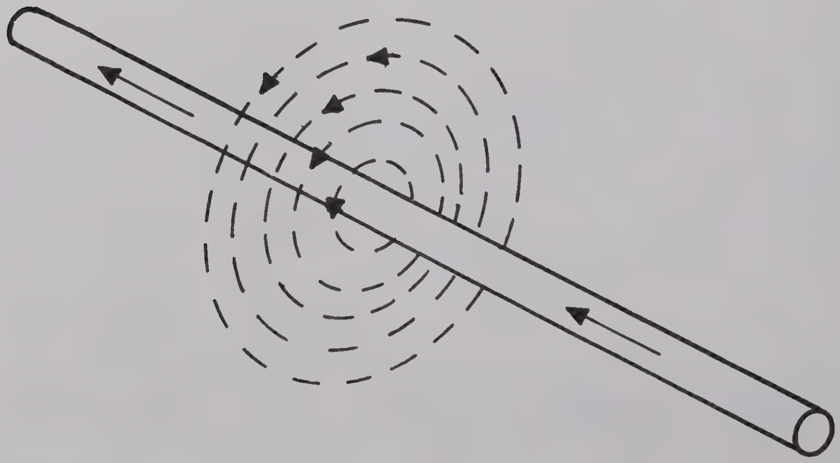
25. False — Even the poorest conductor of magnetic lines is unable to insulate an object from the effects of a magnetic field. Magnetic shielding is accomplished by surrounding the object to be protected with a low-reluctance material such as soft iron. The magnetic lines then travel through the soft iron around the object instead of through the object itself.

26. electromagnetism

27. circles or rings

28. The reversal of current causes a reversal in the direction of the magnetic field.

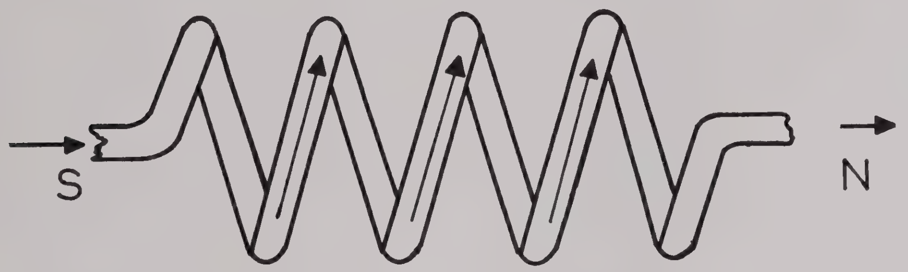
29.

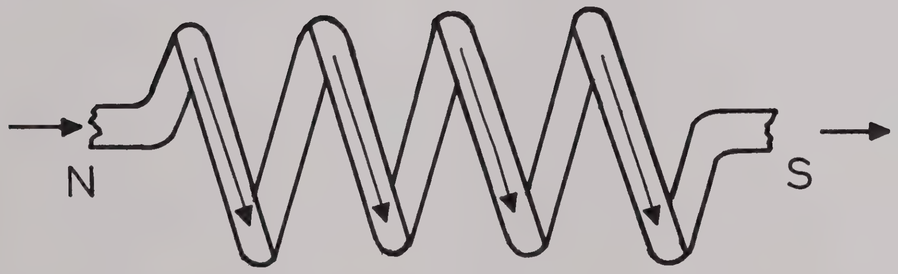


PRACTICE EXERCISE SOLUTIONS (Continued)

30. combine with or reinforce. — This strengthens the overall magnetic field of a coil.

31. Using the Left Hand Rule, the back of your hand will face you in the upper diagram, and the front of your hand will face you in the lower diagram.





32. Ampere-turns.

33. Use a soft iron core in the coil.

34. (c) armature.

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1028A&B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1028B

1. A - MAGNETS WHICH KEEP THEIR MAGNETISM INDEFINITELY ARE -- PERMANENT.
A temporary magnet is one that gains and loses its magnetism easily.

2. D - AROUND EACH MAGNET IS -- A MAGNETIC FIELD.
The magnetic field is actually associated with the orbiting electrons of the material.

3. D - A MAGNETIC FIELD IS THOUGHT OF AS BEING MADE OF -- LINES OF FORCE.
The Weber is the unit of measure of the number of magnetic lines of force and is equal to 10^8 lines of force.

4. C - OUTSIDE THE MAGNET, THE DIRECTION OF THE LINES OF FORCE ARE ASSUMED TO BE -- FROM THE NORTH POLE TO THE SOUTH POLE.
Inside the magnet, the direction of the lines of force are from the south pole to the north pole.

5. D - WITH RESPECT TO MAGNETIC POLES, -- LIKE POLES REPEL.
The law of magnetism states that like poles repel and unlike poles attract.

6. A - AS THEY MOVE AWAY FROM A MAGNETIC POLE, THE DENSITY OF THE LINES OF FORCE -- DECREASES.
The density of the magnetic lines of force decreases as the square of the distance.

7. B - THE OPPOSITION WHICH A MATERIAL OFFERS TO THE PASSAGE OF MAGNETIC LINES OF FORCE IS -- RELUCTANCE.
Reluctance in a magnetic circuit is like resistance in an electric circuit.

8. D - WHEN CURRENT IS PASSED THROUGH A WIRE -- A MAGNETIC FIELD APPEARS ABOUT IT.
The left hand current rule can be used to determine the direction of the generated magnetic field.

9. A - WITH A CURRENT IN A COIL OF WIRE -- IT BECOMES A MAGNET.
The strength of the magnetic field depends upon the number of turns in the coil and the amount of current passing through the coil.

10. C - THE AMPERE-TURN IS THE UNIT OF MEASURE FOR -- THE MAGNETOMOTIVE FORCE OF A CURRENT-CARRYING COIL.
The magnetomotive force in ampere turns is equal to the coil current times the number of turns ($F = NI$).

1028A

All explanations are the same as for 1028B except for those listed below.

2. D - ABOUT EACH MAGNET IS -- A MAGNETIC FIELD.
The magnetic field is actually associated with the orbiting electrons of the material.

6. A - WHEN FURTHER FROM A MAGNETIC POLE, THE DENSITY OF THE LINES OF FORCE -- DECREASES.
The density of the magnetic lines of force decreases as the square of the distance.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1028B

Example: A cat has
A ☐
B ☐
C ☐
D ■

A. 3 legs. B. 2 legs. C. 1 leg. D. 4 legs.

1. A ☒ B ☐ C ☐ D ☐

Magnets which keep their magnetism indefinitely are
(A) permanent. (B) soft iron. (C) temporary. (D) not made of alnico.

2. A ☐ B ☐ C ☐ D ☒

Around each magnet is
(A) a negative charge. (B) a current. (C) a voltage. (D) a magnetic field.

3. A ☐ B ☐ C ☐ D ☒

A magnetic field is thought of as being made of
(A) magnetomotive force. (B) south poles, but not north poles. (C) reluctance. (D) lines of force.

4. A ☐ B ☐ C ☒ D ☐

Outside the magnet, the directions of the lines of force are assumed to be
(A) across each other. (B) from the south pole to the north pole. (C) from the north pole to the south pole. (D) always east and west.

5. A ☐ B ☐ C ☐ D ☒

With respect to magnetic poles,
(A) unlike poles repel. (B) like poles attract. (C) two south poles attract. (D) like poles repel.

6. A ☒ B ☐ C ☐ D ☐

As they move away from a magnetic pole, the density of the lines of force
(A) decreases. (B) increases. (C) never changes. (D) may decrease or increase depending upon the polarity.

7. A ☐ B ☒ C ☐ D ☐

The opposition which a material offers to the passage of magnetic lines of force is
(A) electromagnetism. (B) reluctance. (C) magnetomotive force. (D) permanent magnetism.

8. A ☐ B ☐ C ☐ D ☒

When current is passed through a wire,
(A) the magnetic field stops the current. (B) a compass needle is never deflected. (C) the wire points north. (D) a magnetic field appears about it.

9. A ☒ B ☐ C ☐ D ☐

With a current in a coil of wire,
(A) it becomes a magnet. (B) there is no magnetic field until a piece of iron is put into the core. (C) the magnetic circuit is broken. (D) the more turns, the weaker the field.

10. A ☐ B ☐ C ☒ D ☐

The ampere-turn is the unit of measure for
(A) reluctance. (B) the mmf of a permanent magnet. (C) the magnetomotive force of a current-carrying coil. (D) flux density.

EXPERIMENT 2

MAGNETS AND ELECTROMAGNETS

PARTS NEEDED

1 - Design Console
1 - Electromagnetic Coil
1 - Permanent Magnet
- Modular Connectors

1 - 10Ω, 1 W, Resistor
1 - Diode
- Hookup Wire

OBJECTIVE

The purpose of this experiment is to investigate the action of an electromagnet and demonstrate the laws of magnetism.

PROCEDURE

1. Connect the circuit shown in Figure 2-1. The diode is used to convert the ac voltage from the transformer to a dc voltage. An electromagnet must be connected only to dc. Heavily "tin" the ends of the coil leads to stiffen them for easy insertion into the modular connectors. Place the coil in a horizontal position on the design console.

2. With the diode connected as shown in Figure 2-1, the polarity of the applied voltage will be as shown at points A and B. Using this information and the left hand coil rule, determine the north pole of the coil. Mark this end in some manner, such as with a small piece of tape, paint, etc.

3. Apply power to the circuit by placing the design console on/off switch to the on position. Attempt to place the permanent magnet in the hole in the middle of the coil. If the permanent magnet is repelled, turn it around and reinsert it in the coil. When the permanent magnet stays inside the coil, mark the end pointing to the north pole of the coil. This end is the south pole of the permanent magnet. Turn the design console on/off switch to the off position after the poles of the permanent magnet are identified.

4. Place the permanent magnet inside the coil, but this time leave most of it sticking out of one end. Gently hold onto this end. Be sure the south pole points toward the north pole of the electromagnet. Turn the design console on/off switch to the on position. The permanent magnet should be pulled into the center of the coil. Turn off the design console power.

5. Insert the permanent magnet into the coil as in Step 4, but this time place its south pole opposite to the north pole of the electromagnet. Turn the design console on/off switch to the on position. The magnet should now be ejected

from the coil. Turn the design console on/off switch to the off position.

6. Gently hold the permanent magnet inside the coil with its south pole pointing to the north pole of the electromagnet. Reverse the connectors of the coil to points A and B. This changes the direction of the current, and also the poles of the electromagnet. Turn the design console on/off switch to the on position. Since the poles of the electromagnet have been reversed, the magnet should be repelled. Turn the design console on/off switch to the off position.

CONCLUSION

In this experiment we see that unlike poles attract and like poles repel. Also, the magnetic poles of a coil are dependent on the direction of current flow through the coil.

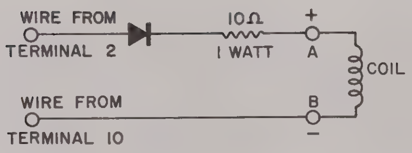

FIGURE 2-1

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9502-2A
EXAMINATION CHECK SHEET

1. B - WHEN LIKE POLES OF TWO MAGNETS ARE BROUGHT TOGETHER, -- THE MAGNETS REPEL.
One of the basic laws of magnetism indicates that like poles repel.

2. A - WHEN UNLIKE POLES OF TWO MAGNETS ARE BROUGHT TOGETHER, -- THE MAGNETS ATTRACT.
One of the basic laws of magnetism indicates that unlike poles attract.

3. A - ONE FACTOR WHICH DETERMINES THE POLES OF AN ELECTROMAGNET IS -- THE POLARITY OF APPLIED VOLTAGE.
The polarity of the applied voltage will determine the direction of current through the coil. The direction of current is one factor determining the poles of an electromagnet.

4. C - ANOTHER FACTOR WHICH DETERMINES THE POLES OF AN ELECTROMAGNET IS -- THE DIRECTION OF THE WINDINGS.
The direction of the windings also determines the direction of current and hence determines the poles of the electromagnet.

5. B - IF THE NORTH POLE OF AN ELECTROMAGNET IS BROUGHT CLOSE TO THE SOUTH POLE OF A PERMANENT MAGNET, THE RESULTS WILL BE OPPOSITE TO THE REACTION WHEN TWO PERMANENT MAGNETS ARE BROUGHT TOGETHER WITH THE SAME ORIENTATION. -- FALSE.
An electromagnet and a permanent magnet will react in the same way.

ALTERNATING CURRENT

1031

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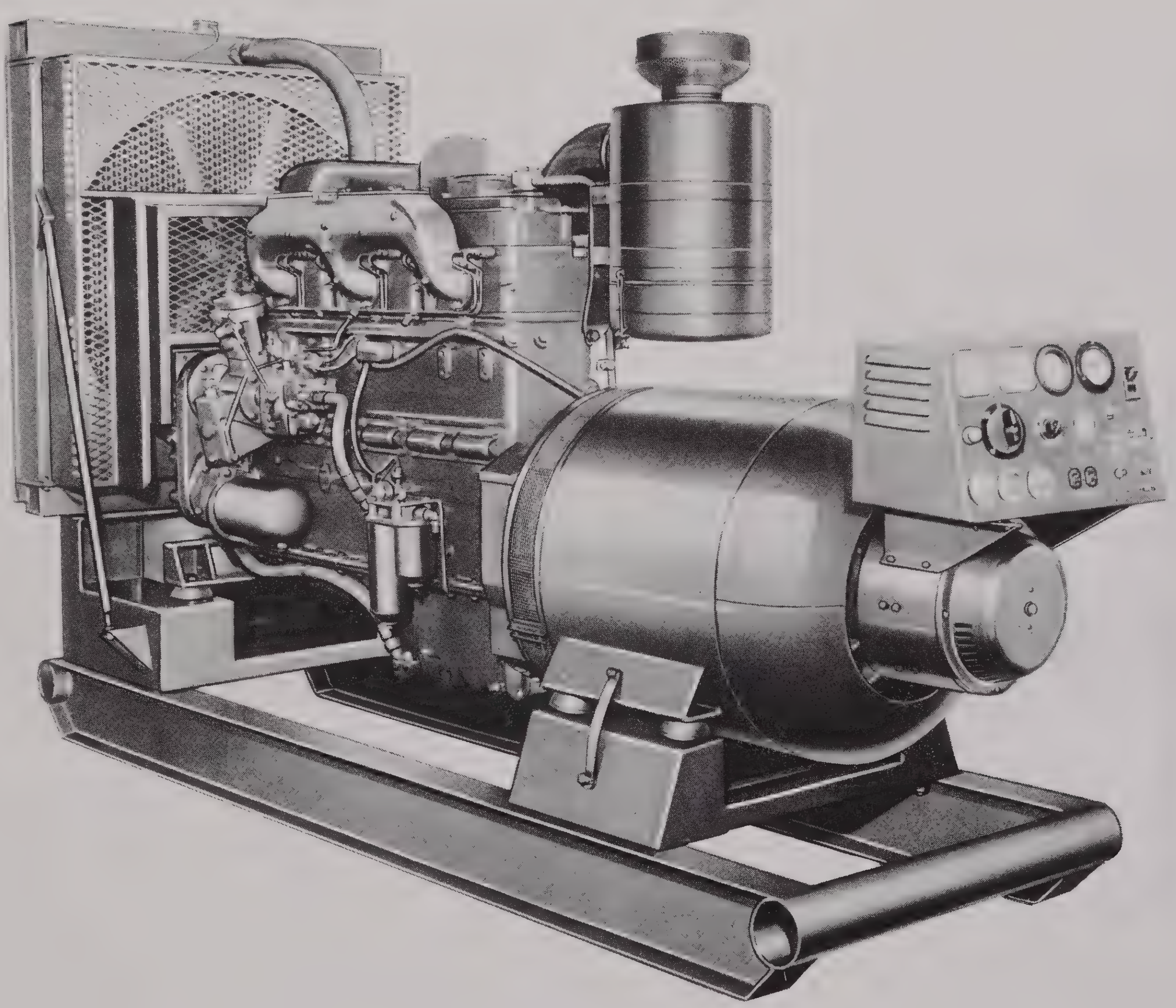

Electric energy is generally distributed in the form of alternating current. Diesel or gasoline engine-driven alternators, like this one, are used to supply power during emergencies. Similar units serve as the sole power source in remote locations.

Courtesy Kohler Co.

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> *The only people who achieve much are those who want knowledge so badly that they seek it while the conditions are still unfavorable. Favorable conditions never come.*
>
> *—C. S. Lewis*

ALTERNATING CURRENT

The electricity supplied to our homes, schools, businesses and industries is generally alternating current or ac. Also, the radio and television signals that travel from a transmitting station to a receiver are produced by alternating currents in the transmitting antenna. In this lesson, we will investigate the methods of generating alternating current and learn some of the characteristics of this type of power as compared to direct current power.

ELECTROMAGNETIC INDUCTION IN A WIRE

As we have learned, magnetism can be produced by passing an electric current through a conductor. The reverse of this is also true: A conductor which moves across or "cuts" a magnetic field develops a flow of electrons. Also, a magnetic field that moves across a conductor develops a current. This is the principle of **ELECTROMAGNETIC INDUCTION,** which is the process of developing a voltage in a wire that is either cutting or being cut by a magnetic field. This idea is the basis for most electric **GENERATORS** and similar power sources.

Figure 1 shows a wire cutting (moving upward through) a magnetic field. The wire is shown as a heavy, straight line. A magnetic field exists between the north and south poles of the magnets in the drawing. Cutting this field with a wire causes a voltage to appear between points A and B.

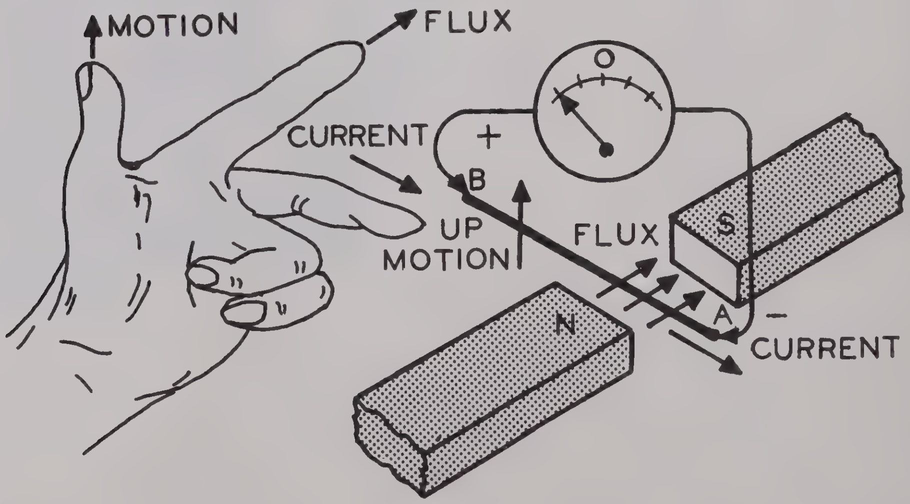


Figure 1

A zero-center meter is attached to points A and B. This meter indicates the polarity of the induced voltage. With no induced voltage, the meter rests over the zero at the center of the scale. An induced voltage will cause the meter pointer to move away from zero. The direction the pointer moves depends on the polarity of the voltage.

The fingers of the left hand can be used to determine the direction of the current induced in the wire, as shown in Figure 1. The thumb points in the direction of conductor movement, the forefinger points in the direction of magnetic flux, and the bent middle finger points in the direction of the induced current. This is called the **LEFT HAND GENERATOR RULE.** When the wire is pulled upward as shown in Figure 1, the induced electron flow through the wire is from point B to point A. When the conductor is moved downward as in Figure 2, the induced electron flow is in the opposite direction, through the wire from point A to point B.

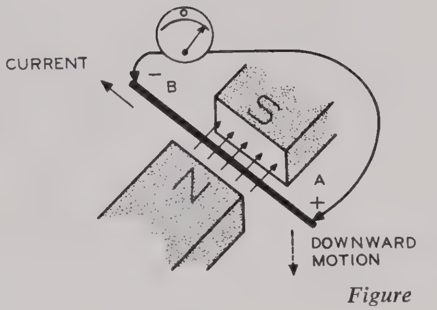


Figure 2

The conductor must cut the magnetic field in order for a voltage to be induced in the conductor. Either the field or the conductor can be moved. The result is the same as long as cutting occurs.

FACTORS AFFECTING THE INDUCED VOLTAGE

The strength of the induced voltage depends on several factors. Two of these are the length of the conductor cutting the field and the rate at which the magnetic lines are cut.

The conductor cutting the field may have different shapes. It may be a straight wire. More often, it is a coil or a loop or loops of wire. No matter what the shape, the principle is the same. The longer the part of the conductor cutting the magnetic field, the greater the voltage induced in the conductor.

The amount of induced voltage also depends on the rate of cutting of the magnetic field. The rate of cutting depends on the speed of conductor movement and the strength of the field. The greater the conductor speed, the greater the induced voltage. Slowing down the speed of the conductor decreases the cutting rate, lowering the induced voltage.

We can also change the induced voltage by changing the field strength. Changing the field strength actually changes the number of lines cut by a moving conductor during a certain period of time. If we increase the field strength, there are more lines of force for a given area. In other words, the lines are closer together. Packing more lines in the same space means that the conductor will cut more lines for each inch of travel. The more lines cut, the greater the induced voltage.

What happens when the field strength is decreased? This is similar to thinning out the lines of force. As a result, fewer lines of force will be cut for each inch traveled. Cutting fewer lines results in a smaller induced voltage.

Another factor that can affect the rate of cutting is the angle at which the lines are cut. The magnetic field is shown by arrows between the poles of the magnets in Figure 3. The small circle is an end view of the wire, which extends into the page. If you move the wire in direction A, you are moving it straight across the field. Direction A is the shortest path across the field. Therefore, the wire moving in this path cuts the greatest number of lines per inch traveled.

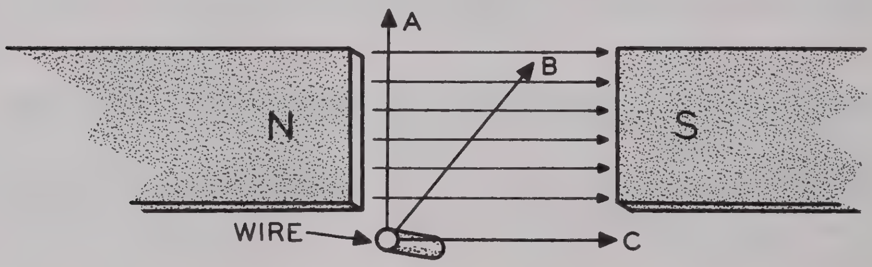


Figure 3

Let's change the angle of cutting and see what happens. Suppose that you move the wire along the path marked B. The wire travels farther between lines of force, so it cuts fewer lines even though it travels the same distance as it did in path A. Thus, the field looks weaker to the wire along path B. Less voltage will be induced in a wire moving along this path than along path A, unless the wire moves faster. If the conductor moves along path C, no magnetic lines of force are cut and there is no voltage induced into the conductor.

What happens if a wire is moved back and forth across a magnetic field? To find out, refer back to Figures 1 and 2. Pulling the wire up through the field causes a voltage with the polarity shown in Figure 1. Pushing the wire down through the field causes the polarity of the induced voltage to reverse. This is shown in Figure 2. The direction of cutting determines the polarity of the induced voltage.

Considering all of these effects, the following four factors control the amount of induced voltage:

1. The speed of the motion, or how fast the magnetic lines and the conductor move with respect to each other. The greater the speed, the greater the induced voltage.

2. The length of the wire that cuts through the magnetic field. The longer the wire, the greater the induction. In the case of a coil, the more turns, the greater the induced voltage.

3. The strength of the magnetic lines, or the number of magnetic lines per unit area. The stronger the flux, the greater the induced voltage.

4. The angle of cutting the magnetic lines changes the induction. The more nearly the wire cuts squarely across the lines, the larger the induced voltage.

These factors can be summed up into one simple sentence which states: **THE INDUCED VOLTAGE IS DIRECTLY PROPORTIONAL TO THE RATE OF CUTTING THE LINES OF FORCE.** The term "rate" means the number of magnetic lines which are cut by the conductor per second. The rate can be increased by increasing the speed of cutting, the length of the conductor cutting the field, the strength of the flux, or the angle of cutting.

An important point to remember is that the action induces a voltage in the coil or conductor, and if the conductor that cuts the magnetic flux is a part of a complete electric circuit, then the induced voltage will cause a current in the circuit. You may read or hear a lot about induced current, but to be technically correct, it is a current caused by an induced voltage.

A SIMPLE AC GENERATOR

We will now put these basic ideas together to explain a simple ac generator. An ac generator is often called an **ALTERNATOR.** Figure 4 shows a simple device which can be used to generate an ac voltage. The north pole of one magnet is placed near the south pole of another magnet. A magnetic field exists between the two poles. The pole faces of the magnets are formed so that a loop of wire will easily turn between them. The magnets are called FIELD MAGNETS, because they provide the magnetic field for the alternator. Another term occasionally used is FIELD POLES. Electromagnets are generally employed in ac generators or alternators to develop the magnetic field. These electromagnets are usually referred to as the **FIELD.**

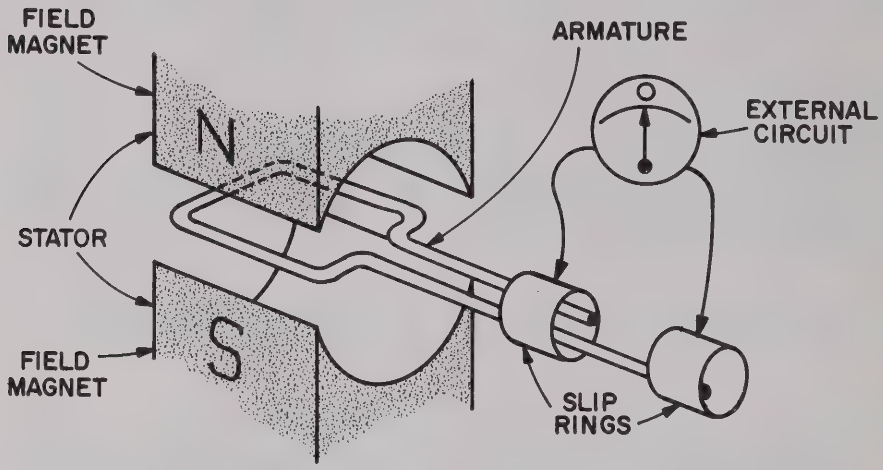


Figure 4

In the previous explanations, we cut a field with a single wire. In Figure 4, the wire is formed into the shape of a loop. The voltage of this alternator appears between the ends of the loop. Connections are made to the ends of the loop through rings, called **SLIP RINGS,** which rotate with the loop. One slip ring is connected to each end of the loop attached to it. The external circuit is connected to the slip rings by contacts called brushes (not shown in the figure), which are held against the rings.

That part of an alternator in which the induced voltage is produced by induction is known as the **ARMATURE.** In the simple alternator of Figure 4, the loop is the armature. The turning or rotating part of the generator is the **ROTOR.** In Figure 4, the armature is the rotor. The stationary part of the alternator is called the **STATOR.** The stator in Figure 4 consists of the field magnets.

The output of an ac generator is an **ALTERNATING VOLTAGE**, or ac voltage. This means that the output voltage of the alternator keeps changing as the rotor moves. The ac generator has an output voltage which keeps

The following Practice Exercise questions cover the subjects which you have just studied. They are:

ELECTROMAGNETIC INDUCTION IN A WIRE

FACTORS AFFECTING THE INDUCED VOLTAGE

1. Moving a metal screwdriver through a magnetic field induces a voltage between points on the blade. True or False?

2. Could a voltage be induced in a wire as it is moved through the earth's magnetic field?

3. What would happen to the induced voltage in Figure 1 if the wire was moved rapidly up and down?

4. Either the ________ or the ____________ ___________ can be moved to induce a voltage in a wire.

5. Moving both the magnetic field and the wire at the same speed in the same direction (a) produces an induced voltage in the wire, (b) results in no induced voltage.

6. A voltage is induced in a wire any time it either cuts or is cut by a magnetic field. True or False?

7. Two wires are cut along their entire length by a moving magnetic field. One wire is 1 inch long and the other is 2 inches long. Which one will have the greatest voltage induced across it?

8. What factors affect the amount of voltage induced in a coil by a magnetic field?

9. Increasing the conductor speed while reducing the magnetic field strength to zero causes the amount of voltage induced in the conductor to (a) increase, (b) decrease.

10. **Compared to moving the wire of Figure 3 along line A, moving the wire along line B at the same speed results in (a) greater output, (b) less output.**

11. **A wire moved rapidly along line C of Figure 3 has (a) a large amount of voltage induced in it, (b) almost no voltage induced in it.**

12. **How much voltage is induced in a wire held at the center of a stationary magnetic field?**

13. **Moving a wire back and forth across a magnetic field causes the voltage induced between its ends to vary in step with the changes in wire motion. True or False?**

changing polarity as the loop is revolved or rotated. The changing ac voltage in turn develops an **ALTERNATING CURRENT** in a resistive load.

Let's see what happens when the armature (loop) of Figure 4 is revolved. Figure 5 shows four positions of the loop. The loop is traveling in a counter-clockwise direction as shown by the arrows in Figure 5.

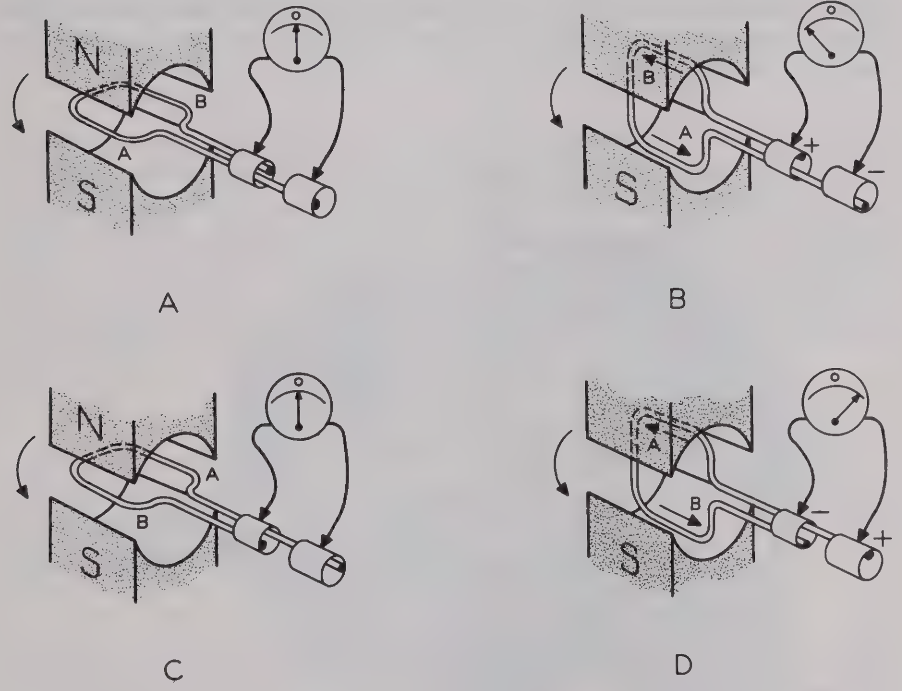


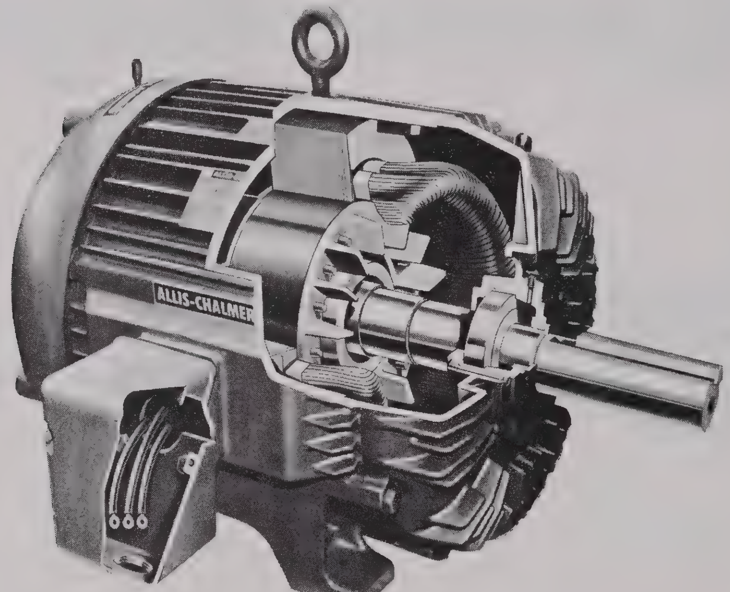
Figure 5

Starting with Figure 5A, the wires of the loop are farthest from the field magnet poles. At this point, the two sides of the loop are moving parallel to the field. This results in the least cutting of lines of force. When the loop is as shown in Figure 5B, it is cutting many more lines of force. The loop is now moving across the faces of the magnets. Path A of Figure 3 shows a conductor moving directly across the face of a magnet. This is the shortest distance across the field. Therefore, the field appears the most tightly packed along this path.

By the time it has reached the position of Figure 5C, the loop has made one-half a revolution. Figure 5C is similar to Figure 5A. As in Figure 5A, there is very little cutting of the field in Figure 5C. As a result, the voltage induced in the loop is minimum at this point.

The loop makes one-fourth of a revolution between Figures 5C and 5D. The loop is again cutting the greatest number of lines. Therefore, the induced voltage again is maximum at this point.

We have seen how the position of the turning loop affects the amount of cutting. Now let's look at the induced voltage. One side of the loop is attached to one slip ring and the other side of the loop to the other slip ring. A sensitive meter is connected across the slip rings of Figure 4. This meter is similar to the one in Figures 1 and 2. It will indicate the amount and polarity of the induced voltage at the slip rings. You will see how this system develops an alternating voltage.



This photo shows the internal construction of a large motor designed to operate from an alternating current (ac) source.
Courtesy Allis-Chalmers

The direction of loop travel is counterclockwise, as before. In Figure 5A, side A of the loop is midway between the north and south poles, nearing the south pole. As explained before, no cutting occurs in this position. Therefore, no voltage is induced in the loop. As a result, the meter attached to the slip rings indicates zero at the center of the meter scale.

After the loop has made one-quarter of a revolution, it is in the position shown in Figure 5B. With maximum cutting as the loop moves through this spot, maximum voltage is induced in the loop. The direction of the electron flow is shown by the arrows along the wires. This results in the slip rings having the polarities shown. The meter indicates that a voltage is present, the pointer having moved to the left of zero.

Moving the loop counterclockwise another quarter turn brings it to the position shown in Figure 5C. This is almost the same position as was shown in Figure 5A. In this position, there is minimum cutting of the field and, therefore, minimum induced voltage at the slip rings. As a result, the meter pointer rests at zero.

Another quarter turn brings the loop to the position shown in Figure 5D. Again, maximum cutting occurs. Maximum induced voltage appears across the slip rings. Notice that the polarity is opposite to the polarity shown in Figure 5B. The reason is that the loop is turned around. Wire A is now on top and wire B is now on the bottom. Direction of electron flow is shown by arrows along the wires. Since the polarity of the induced voltage is the opposite of that in Figure 5B, the meter pointer is on the other side of the zero mark.

The output of this simple alternator is taken between the slip rings. The meter shows that a voltage appears between the rings when the loop is as shown in Figure 5B and 5D. Since the polarity of this induced voltage changes, the generator is producing an ac voltage.

Now that we have a basic idea of how an alternator works, let's take a closer look at it. For this, we will use Figure 6. Here we have divided one complete revolution into twelve parts. It starts at position 0 and ends at position 12. Positions 0 and 12 are the same. We will again use a single loop, as we did in Figure 5, with the sides of the loop marked A and B. Since we are looking into the end of the loop, wires A and B appear as circles rather than lines. (The slip rings are not shown, since they are between us and the loop.) The loop is being turned in a counterclockwise direction.

In the center of Figure 6 is a graph. The induced voltage at each position of the loop is marked on the graph. The graph pictures the changes in output of the alternator for one complete revolution.

The center horizontal line of the graph is marked "0." A dot on this line indicates zero voltage. For this graph, we will consider the polarity of wire A of the loop with respect to wire B. When wire A is more positive than wire B, the dot for that position will be above the zero line. The opposite is

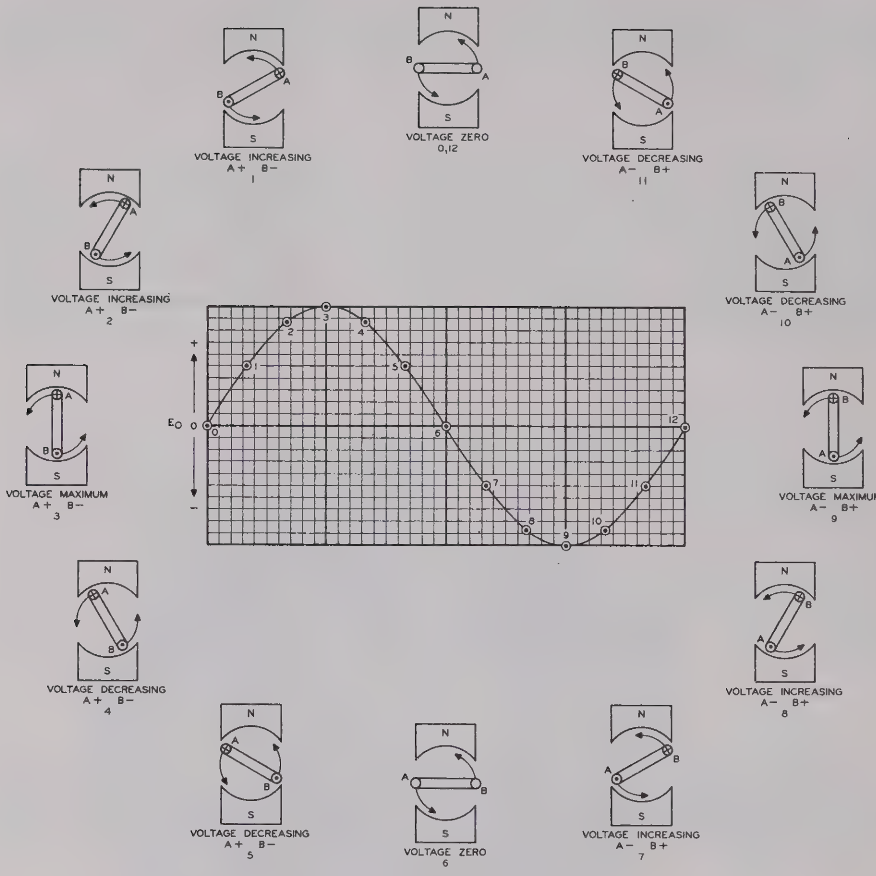


Figure 6

true when wire A is more negative than wire B. Then the dot will be below the zero line.

The graph shows us at least three things. It shows when the alternator output is zero. It shows the rate at which the induced voltage increases or decreases. Also, it shows the polarity of wire A with respect to wire B. Whichever wire is closer to the north pole of the alternator field will be positive with respect to the other wire.

Position 0 is at the top of Figure 6. Wires A and B of the loop are midway between the poles. There is minimum cutting of the field in this position, so there is no induced voltage. Therefore, a dot is placed on the zero line of the graph for position 0.

Position 1 shows the loop moved one-twelfth of a turn counterclockwise from position 0. Wire A is now nearing the north pole. Wire B is nearing the south pole. The loop is now cutting more lines of force than it did as it passed through position 0. As a result, a voltage is induced in the loop. The slip ring attached to wire A is now positive with respect to the one attached to wire B. Because of this polarity, the dot for the induced voltage at position 1 is above the zero line in the graph of Figure 6.

One-twelfth of a revolution later, the loop is passing through position 2. The loop is cutting even more lines now. As a result, the induced voltage is greater. Wire A is still cutting across the face of the north pole, while wire B is cutting across the south pole. As a result, wire A is still positive with respect to wire B. On the graph, the dot for position 2 is farther above the zero line than that for position 1.

As the loop passes through position 3, maximum voltage is induced between the slip rings. This is because the loop is now cutting the most lines of force. Wire A is moving past the center of the north pole of the magnet. Therefore, wire A is still positive with respect to wire B. The dot for position 3 is at the top of the graph. This indicates maximum voltage with this polarity.

We now leave the point of maximum cutting. Wire A is still closer to the north pole of the magnet. This means that the dots for positions 4 and 5 will still be above the line. The loop cuts fewer lines of force as it moves away from the centers of the poles, and the induced voltage becomes less.

In positions 2 and 4, the loop is about the same distance from the centers of the poles. Wire A is slightly to the right of center of the north pole in position 2. In position 4, wire A is the same distance on the other side of the center of the north pole. The induced voltage is the same as the loop passes through either of these two spots. Notice that the dots for positions 2 and 4 are the same distance from the zero line on the graph.

Positions 1 and 5 also have something in common. The loop is the same distance from the centers of the poles. In position 1, wire A is at the right edge of the north pole. Wire A is at the left edge of the north pole in position 5. The induced voltage is the same in both cases, and the dots for these two positions are the same distance above the zero line.

When the loop has made half a revolution, it is at position 6. This is the inverse of position 0. Wires A and B of the loop are changed around. As before, there is almost no cutting of the field as the loop moves through this spot. No voltage is induced in the loop. The dot for this position is placed on the zero line of the graph.

The second half-revolution looks like an upside down copy of the first half. The reason for this is that wire B is now going past the north pole. Wire B is now positive with respect to wire A. This means that the points on the graph for positions 7 to 11 are below the zero line, since the points show the polarity of wire A with respect to wire B.

From position 7 to position 9, the amount of cutting keeps increasing. Therefore, the induced voltage keeps rising until it reaches its maximum. This occurs at position 9. Notice that the points on the graph are now below the zero line, showing that the polarity of the voltage across the loop has changed. The amounts of voltage generated at positions 3 and 9 are the same, and the dots at these points are the same distance from the zero line.

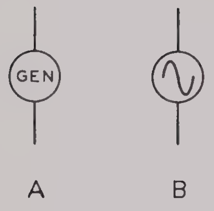


Figure 7

The amount of cutting becomes less and less as the loop is turned further. Therefore, the output voltage becomes smaller as the loop is moved from position 9 to position 12. Position 12 is the same as position 0.

Two common generator symbols are shown in Figure 7. The one shown in Figure 7A is often used to represent a mechanical generator or alternator. The symbol of Figure 7B is generally used for an electronic ac generator.

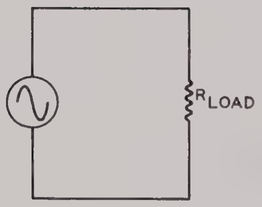


Figure 8

Figure 8 shows an alternator connected to a load. The load, R_{LOAD}, is shown as a resistor. The voltage developed by the generator will force an alternating current through the load when a complete circuit exists.

A SINUSOIDAL WAVEFORM

The curve of output voltage shown in Figure 6 has a special shape. Notice the smooth rise and fall of this curve. It has no sharp bends. It has no straight portions.

Let's review how we made this curve. We divided one rotation of the alternator loop into twelve parts. They were labeled positions 0 to 11 (position 12 was the same as position 0). As the loop of Figure 6 was turned in its magnetic field, a voltage was induced between its ends. This voltage was not the same for all positions of the loop, so we plotted them on the graph of Figure 6. When wire A was positive with respect to wire B, the value of the induced voltage was plotted above the zero line. The greater the induced voltage, the farther the plotted point was from the zero line. When wire B was positive with respect to wire A, the point for that position was plotted below the line. The curve was generated from rotation of the loop. If we continued the rotation, we would develop the curve of Figure 9.

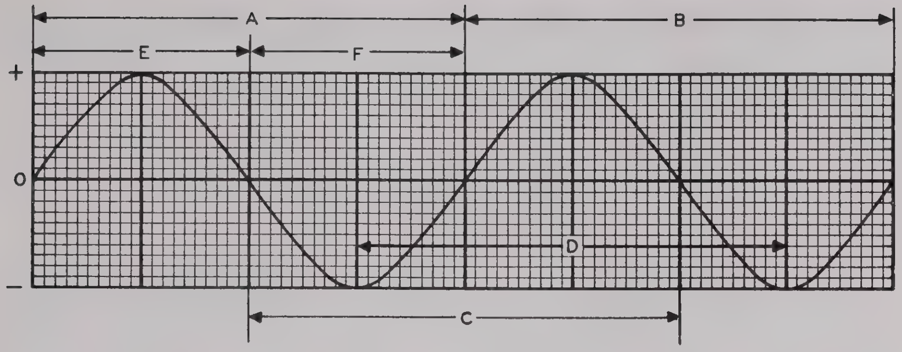


Figure 9

As you would expect, Figure 9 looks like two graphs of Figure 6 laid end to end. This curve is often called a waveform. The way the curve goes up and down is like a water wave on a lake. This curve has a special name. It is called a **SINUSOIDAL** curve. Sometimes, this curve is called a sinewave or sine curve. A sinusoidal curve is a mathematical relationship plotted out on a graph. The plot of an alternator voltage and a sinewave is the same.

Oscilloscopes provide a means of observing the waveforms in an alternating current circuit.
Courtesy Heath Co.

The sine curve can also represent current. Consider Figure 8 again. If the alternator has a sinusoidal voltage output, current will flow back and forth through the load. It will change in a sinusoidal fashion also.

THE AC CYCLE

Figure 9 is a curve which goes above and below the zero line. It alternates or changes twice for each turn of the generator loop of Figure 6. Two turns of the loop are represented in Figure 9. The curve goes above the zero line twice. It also goes below the zero line twice. The current alternates or changes four times during the two turns of the loop. We could continue the curve for more turns. Regardless of how far we continue the curve, there will be TWO ALTERNATIONS for EACH TURN or revolution of the loop.

The voltage corresponding to one complete turn of our loop is called a **CYCLE.** A cycle is one complete change of curve values. The curve of Figure 6 shows one cycle. Figure 9 is divided into two cycles, labeled A and B. Let us look at cycle A. It begins at the zero line, rises to its maximum value above the line, returns to zero, goes to its maximum value below the line, and then returns to zero. Cycle B is a copy of cycle A.

From our definition, we can say that the portion of the curve labeled C is also a cycle. It is a complete set of values. The curve begins at zero, goes downward, returns to zero, rises above zero, and then returns to zero.

A cycle is often subdivided. Each cycle consists of two alternations. An **ALTERNATION** is one-half of a cycle. It is often stated as the rise and fall of current or voltage in one direction. The portion of cycle A that is labeled E is an alternation. F is the other alternation of cycle A. Portion E could be called a positive alternation while portion F could be called a negative alternation, because portion E has only positive values and portion F has only negative values.

Just as a curve can be divided into cycles and alternations, there are also ways of referring to the height of a curve. The value of voltage or current at any particular point is called the **INSTANTANEOUS VALUE**. This is because time passes while the alternator loop is being revolved. Each point on the curve occurs only once per cycle and it occurs at a particular instant of time. In Figure 9, the zero time point is at the left end of the graph; as time passes, the alternator armature revolves and the instantaneous value of the induced voltage varies, first in the positive direction and then the negative.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

A SIMPLE AC GENERATOR

A SINUSOIDAL WAVEFORM

14. How many magnets are required to produce the magnetic field of Figure 5A?

15. What is the purpose of an ac generator?

16. The loop cuts the magnetic field in a generator. True or False?

17. Greatest output occurs when the loop is in the position shown in (a) Figure 5A, (b) Figure 5B, (c) Figure 5C.

18. From where is the output of an ac generator taken?

19. Why is the output of the generator shown in Figure 5 greatest at positions B and D?

20. Speeding up the motion of the loop will cause the positions of maximum and minimum output to change. True or False?

21. From the graph of Figure 6, is the induced voltage greater at position 2 or position 5?

22. As the loop passes through position 7, the induced voltage makes wire A (a) positive with respect to wire B, (b) negative with respect to wire B.

23. You should expect the output voltage of an ac generator of a power station to look like a rectangular wave when plotted on graph paper. True or False?

24. Draw two electrical symbols for an ac generator.

25. The current changes through a resistive load connected to a generator are in step with the generator output voltage changes. True or False?

26. A sine curve has one rectangular section and one rounded section. True or False?

The curve can be considered to be a great number of points that are very close together; the value (height above or below the zero horizontal line) of a particular point depends upon the instant time selected for examination.

Now, let us look at the sine curve of Figure 10. This curve represents one cycle. It begins at zero, rises to its maximum positive value, decreases to zero, reaches its maximum negative value, and then returns to zero. The amount of voltage from zero to the positive or negative maximum value is called the **PEAK VALUE**. In the case of Figure 10, the peak value is 10 volts. The peak value occurs twice during each ac cycle (one positive peak and one negative peak).

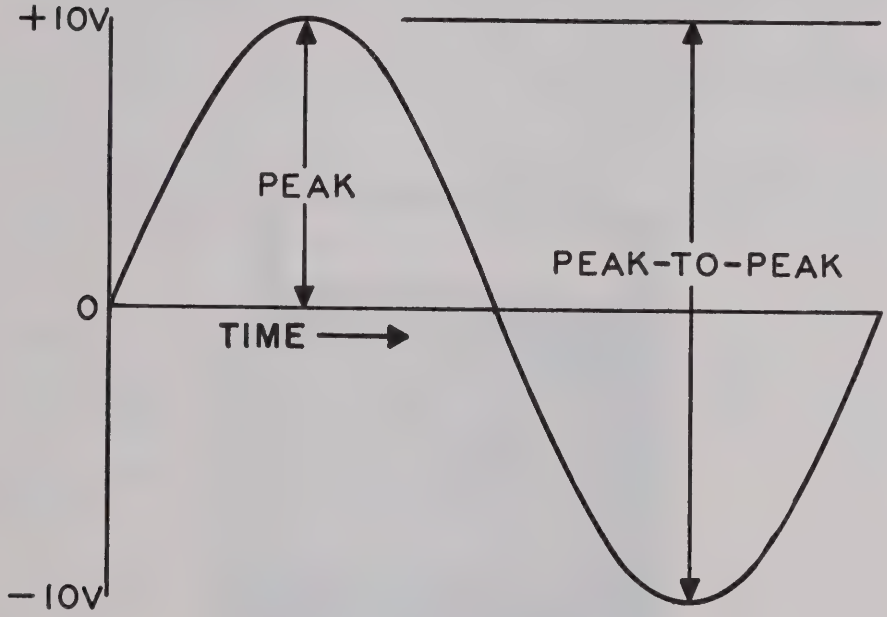


Figure 10

There are times when we would like to know the overall amplitude of a sine curve. This is the voltage difference between the upper and lower maximum points on the curve. Let's look at Figure 10 again. Here, the upper point on the curve represents +10 volts. The lowest point on the curve represents −10 volts. The distance between these points represents 20 volts: 10 volts from +10 to 0, plus 10 volts from 0 to −10. This value of 20 volts is called the **PEAK-TO-PEAK VALUE**.

If we know the peak value of a sinusoidal curve, we can easily find the peak-to-peak value by the following formula:

$$\text{peak-to-peak} = 2 \times \text{peak}. \tag{1}$$

The peak value can easily be found, if we know the peak-to-peak value:

$$\text{peak} = \text{peak-to-peak}/2. \qquad (2)$$

Instruments used to measure either voltages or currents in ac circuits are basically current-measuring devices. Current is measured in amperes. *The ampere is a unit of measurement of a steady rate of flow.* However, during a cycle, the alternating current changes both in value and direction.

Since we would like to measure the current in amperes, we must determine what value of alternating current produces the same effect as a given value of direct current. This determination is made by measuring the heat developed in a pure resistance by a value of direct current and expressing it in terms of the amount of alternating current required to produce the same effect.

This electronic meter is designed so that it can read both the rms or effective value of an ac voltage as well as the peak-to-peak value.

Courtesy Sencore Inc.

Experimentally, it was found that 1 ampere (peak amplitude) of alternating current produces the same heating effect as .707 ampere of direct current. Therefore, an ampere of alternating current is .707 times as effective as an ampere of direct current in terms of heating. Or, the **EFFECTIVE VALUE** of an alternating current or voltage is .707 of its peak value. Notice that we use the same relationship for both alternating currents and voltages. The effective value is also called the **ROOT MEAN SQUARE (rms) VALUE.** The following formulas are used to convert from one value to another:

$$\text{effective or rms} = .707 \times \text{peak, or} \tag{3}$$

$$\text{peak} = 1.414 \times \text{effective or rms.} \tag{4}$$

Unless otherwise stated, ac meters read the measured voltage or current in terms of effective (rms) values. In fact, the operating voltages of home and industrial ac equipment are given in rms values. The power line voltage is also given as an rms value. THIS PRACTICE IS SO COMMON THAT AN ALTERNATING CURRENT OR VOLTAGE IS ASSUMED TO BE GIVEN IN TERMS OF RMS VALUES UNLESS OTHERWISE STATED.

Another term used with ac is the **AVERAGE VALUE**. Figure 11 shows one alternation of an ac sine curve. This alternation goes from 0 to +10 volts and back to zero. The peak value is therefore +10 volts. The rms value is 7.07 volts. As shown in the figure, the average value is less than the rms value but greater than 5 volts. The average value of a sine curve alternation is .637 times the peak value:

$$\text{average} = .637 \times \text{peak.} \tag{5}$$

In Figure 11, the average value is .637 × 10 = 6.37 volts.

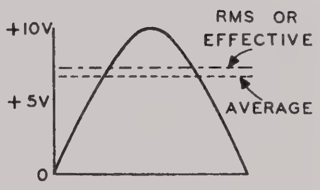


Figure 11

FREQUENCY

The number of cycles that occur in a particular time period is called the **FREQUENCY**, expressed in **HERTZ** (abbreviated **Hz**). The time period is usually 1 second. Therefore, an alternator or generator with an output of 60 cycles per second produces 60 complete cycles of voltage every second, and is said to produce a frequency of 60 hertz. Consider an alternator which produces one cycle of voltage for every revolution. If it is turned at the rate of 1 revolution per second (rps), the output voltage will have a frequency of 1 hertz. The hertz is a recently adopted standard, and many people still designate frequency in cycles per second (cps).

Increasing the speed of the alternator causes the frequency of the output voltage to increase. When the frequency increases, the duration or length of each cycle is shorter. Therefore, frequency and the time length of a cycle are inversely proportional. Decreasing the frequency increases the length (or period) of the cycle.

Frequency is determined by the rotational speed of the alternator and the number of poles. More than one set of magnetic poles is often used in an alternator. If the rotational speed is held steady, the frequency is proportional to the number of sets of poles. A two-pole alternator rotating at 60 rps produces a 60-Hz (or cps) output voltage. A four-pole alternator rotating at 60 rps produces a 120-Hz output voltage.

TYPES OF AC SOURCES

Our simple alternator of Figure 6 contained a single loop and two magnetic poles. The loop was made of a single turn of wire. While practical ac generators operate on the principle illustrated by this simple arrangement, they are usually constructed differently. Instead of a single loop made of a single turn of wire, they have armatures containing many turns of wire. Instead of a single set of poles (field magnets), a practical alternator may have two or more sets of field poles. The poles are usually electromagnets, which are normally fed by a dc power source to provide a steady magnetic field.

You now have some familiarity with the fundamentals of alternating current, including the ac generator or alternator. While this machine is representative of the vast majority of ac power generation equipment used by public utility companies as ac sources, other devices exist that produce ac power, usually on a much smaller scale. Two of these that are often used are the inverter and the oscillator.

Inverters

An **INVERTER** is used to power such things as electric shavers, record players, television sets, tape recorders, public address systems, emergency lighting, etc., from a dc source such as an automobile battery. The use of an inverter makes these ac devices usable wherever a dc source of the proper voltage is available. Figure 12 illustrates the principle of one type of inverter.

This particular device consists of two sections or stages. The first stage is called a vibrator. A vibrator is an electromechanical device. It switches a

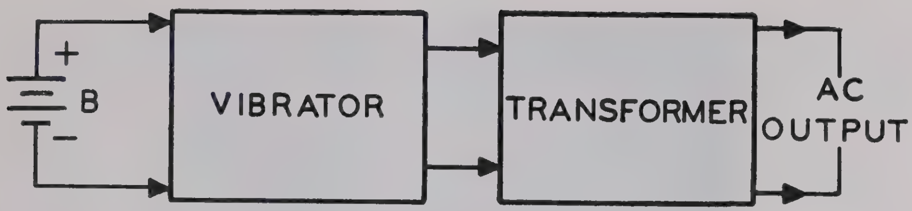


Figure 12

dc power source on and off. In this figure, the dc power source is battery B. The output of the vibrator is fed into a transformer. The transformer uses the switched dc as an input and provides a form of ac voltage as its output. (The next lesson will tell you more about the action of a transformer. These devices do require ac power for operation; dc power just won't provide proper transformer action.) Frequency of the ac output signal is determined by the switching speed of the vibrator and is usually 60 or 400 Hz.

In this example, we used a vibrator to switch the dc power on and off. This switching can also be done with transistors or tubes, in other types of inverters. This is one method of obtaining ac power from a dc source.

Oscillators

An **OSCILLATOR** is also a device for producing ac power from a dc source. Oscillators are generally electronic devices. They use tubes, transistors, resistors, capacitors and inductors. These devices generate frequencies from a few cycles per day to millons of hertz (cycles per second).

Figure 13 is a block diagram of an oscillator. The dc power supply is represented by battery B. The oscillator circuit uses dc power and electronically varies its level. This signal of varying level is then changed to an ac signal. The output of an oscillator is not necessarily sinusoidal.

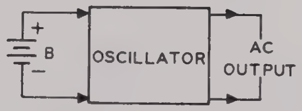
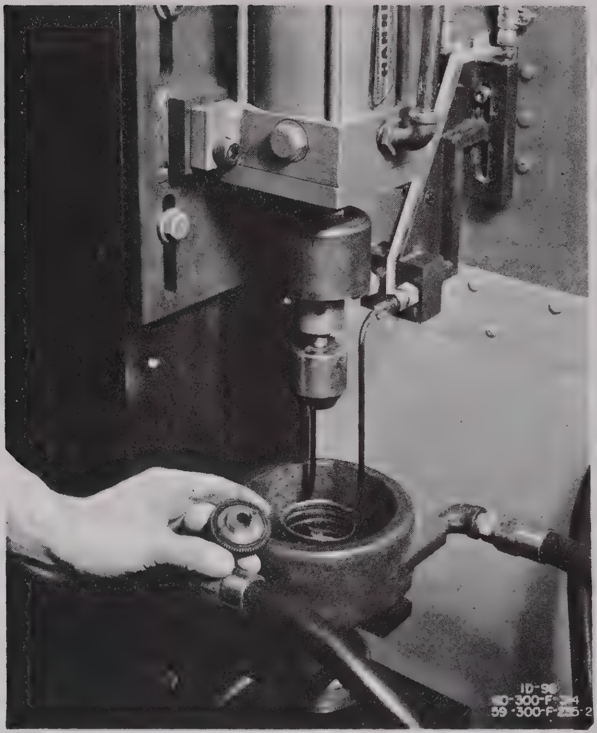


Figure 13

Oscillators are used in many types of electronic equipment. Equipment as common as a radio or as complex as a missile makes use of oscillators. Electronic ovens, radar and television systems all require oscillator circuits for their operation. Many of the test units used by scientists, engineers and technicians rely on oscillators for their operation. One such type of equipment is called a signal generator.



High frequency alternating current is used in this induction heater to heat treat the gear shown.
Courtesy Meta-Dynamics Div.
The Cincinnati Milling Machine Co.

ADVANTAGES OF AC

Although dc power is very desirable in some applications, one of the problems in transmitting dc power is the loss in the connecting wires between the power source (generating station) and the consumer. You already know that the current acts in combination with the wire resistance to generate heat. These heat losses can be reduced by raising the voltage and lowering the value of current at the generating station. While the higher voltage and lower current factors result in the same amount of transmitted power and less losses, unless the power user decreases the voltage at the other end of the line, he will not be able to use equipment that is designed for standard voltages. Many problems and inconveniences can be overcome by using ac power.

This same method of loss reduction (high voltage-low current) is used very effectively in ac power transmission because ac voltages can be easily raised at the sending end (and lowered to the proper values at the receiving end) by transformers. This is one of many ways that ac is more versatile than dc.

Another advantage of ac is that high-frequency alternating current can be radiated or made to travel through space. This makes possible the transmission and reception of radio and television programs. AC power is fed into an antenna system. It is then radiated into the air. Some of these radiated waves cut the receiving antenna. An ac signal is induced in the receiving antenna. This signal is a copy of the one fed into the transmitting antenna. Radar and communication systems also make use of this principle in their operation.

High-frequency energy is also used to heat materials. Modern medicine uses this energy to heat body tissue. In the home, food is baked and cooked in electronic ovens and on electronic stoves in very short periods of time. In industry, metals are heat treated, and plywood panels are bonded together with high-frequency ac energy.

SUMMARY

Whenever a magnetic field either cuts or is cut by a conductor, a voltage is induced in that conductor. This principle is used in the alternator. This device in its simplest form has a single rotating loop cutting a magnetic field. The output of an alternator is an alternating voltage. This voltage depends on the length of wire in the field and the rate of cutting magnetic lines of force.

The amount of voltage developed by a practical alternator is determined by the strength of the magnetic field, the number of turns in the loop, and the speed of rotation. Increasing any or all of these increases the output voltage, and vice versa.

The frequency of the output voltage is expressed in hertz (Hz), which is a measure of the cycles per second. The frequency of the alternator output is proportional to the rotational speed of the device and the number of pole pairs. Doubling the speed doubles the frequency. The greater the frequency, the shorter the duration of one cycle.

An alternator usually develops a sinusoidal voltage waveform. This means that the voltage is constantly changing in polarity and amplitude. The amplitude of a sine curve can be measured in terms of instantaneous, peak, peak-to-peak, rms or effective, and average values.

In addition to the alternator, which is so widely used by public utility companies as an ac source, there are other sources of much smaller amounts of ac power. One of these is the inverter, which changes dc power to ac power. It does this by switching the dc power on and off. The switching device may be a vibrator, transistor or tube. The changing dc signal is then fed into a transformer, producing an ac output. The frequency of the ac output is determined by the switching rate.

Another method of obtaining ac from dc is with an oscillator. An oscillator is an electronic device which uses the output of a dc power supply to produce ac. The oscillator consists of a transistor or tube along with resistors, capacitors, and inductors. The output of an oscillator is not necessarily sinusoidal.

AC power has certain advantages over dc power. We can easily change the amplitude of an ac voltage by passing it through a transformer. Unlike dc, high-frequency ac signals can be transmitted through space. This makes possible radio, television, radar, electronic cooking, the heat treating of metals and woods and other applications.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE AC CYCLE

FREQUENCY

TYPES OF AC SOURCES

INVERTERS

OSCILLATORS

ADVANTAGES OF AC

27. There are two ____________________ in an ac cycle.

28. The curve labeled D in Figure 9 is (a) an alternation, (b) a cycle.

29. What is the peak-to-peak amplitude of a voltage if the peak amplitude of this voltage is 25.5 volts?

30. What is the peak value of a peak-to-peak voltage of 42.8 volts?

31. What is the rms value of the voltage in Practice Exercise 29?

32. The voltage at the wall receptacles in most homes is 120 volts ac. This is an rms value. What are the peak and peak-to-peak values of this voltage?

33. Increasing the rotational speed of an alternator causes its output frequency to (a) increase, (b) decrease, (c) remain the same.

34. If the speed of a 60-Hz alternator is doubled, the frequency of its output voltage will (a) rise to 120 Hz, (b) decrease to 30 Hz, (c) remain the same.

35. Doubling the number of poles ______________ the frequency of an alternator output voltage.

36. An inverter is used to change (a) ac to dc, (b) ac to higher voltage ac, (c) dc to ac, (d) ac to a higher voltage dc.

37. An inverter is usually used to charge an automobile battery. True or False?

38. What is the name of the electronic device used to generate a high-frequency ac voltage using transistors, coils, capacitors, resistors and a dc power supply?

39. Name two advantages of ac over dc.

IMPORTANT DEFINITIONS

ALTERNATING CURRENT (AC) — A current which periodically changes its direction.

ALTERNATING VOLTAGE — A voltage which periodically changes its polarity.

ALTERNATION — One-half of a cycle, consisting of the complete rise and fall of an alternating voltage or current in one direction.

ALTERNATOR — An alternating current generator.

ARMATURE — That part of an electric generator in which the voltage is induced.

AVERAGE VALUE — The average of the instantaneous values through which an alternating voltage or current passes during one alternation. The average value of a sine curve is equal to .637 times its peak value.

CYCLE — The complete set of values through which an alternating voltage or current passes successively.

EFFECTIVE VALUE — The value of an alternating current that produces the same heating effect in a pure resistance as a corresponding value of dc. The effective value of a sine curve is equal to .707 times its peak value. Also called the ROOT MEAN SQUARE (rms) VALUE.

ELECTROMAGNETIC INDUCTION — The process of developing a voltage in a wire that is being either cut by or is cutting a magnetic field.

FIELD — The windings of an electric generator which are supplied with dc to produce the steady electromagnetic field. Generators used for demonstration purposes may use permanent magnets to produce the magnetic field.

FREQUENCY — The number of cycles of alternating voltage or current which occur during a particular amount of time, usually one second.

GENERATORS — Machines used to convert mechanical energy into electric energy. They accomplish this by causing one or a series of interconnected coils to either cut or be cut by a strong magnetic field.

HERTZ (Hz) — The unit of frequency. One hertz is equal to 1 cycle per second (cps).

INSTANTANEOUS VALUE — The value of an alternating current or voltage at any specified instant in a cycle.

IMPORTANT DEFINITIONS (Continued)

INVERTER — An electric or electronic device for producing alternating current from direct current.

LEFT HAND GENERATOR RULE — A method of determining the direction of current flow (polarity) in a conductor, as follows: Extend the thumb, first finger, and second finger of the left hand at right angles to each other. When the thumb is pointed in the direction (upward or downward) of conductor motion as it passes through the magnetic field, and the first finger is pointed to the south pole of the magnetic field (matching the direction of magnetic flux), the second finger will point in the direction of current flow (toward the negative pole or terminal).

OSCILLATOR — An electronic device for converting dc energy into ac energy.

PEAK-TO-PEAK VALUE — The maximum voltage change occurring during one cycle of alternating voltage or current. The total amount of voltage between the positive peak and the negative peak of one cycle, or twice the peak value.

PEAK VALUE — The highest or maximum value of an alternation of alterating current or voltage. This peak value occurs twice during each cycle.

ROOT MEAN SQUARE (rms) VALUE — See EFFECTIVE VALUE.

ROTOR — The rotating member of a generator.

SINUSOIDAL — The graphical plot of the output of an alternator.

SLIP RINGS — The rotating contacts which are connected to the loops of a generator.

STATOR — The stationary coils of a generator.

ESSENTIAL SYMBOLS AND EQUATIONS

peak-to-peak = 2 × peak (1)

peak = peak-to-peak/2 (2)

effective or rms = .707 × peak (3)

peak = 1.414 × effective or rms (4)

average = .637 × peak (5)

PRACTICE EXERCISE SOLUTIONS

1. **True — The screwdriver blade is a conductor, just as is a wire. Whenever a conductor cuts a magnetic field, a voltage is induced between the ends of the conductor.**

2. **Yes — However, the induced voltage would be very small. As a result, the voltage could be difficult to detect and measure.**

3. **Figure 1 shows the wire being pushed up through the magnetic field. The voltage has the polarity shown. Pushing the wire down through the magnetic field produces the polarity shown in Figure 2. The polarity of Figure 1 is opposite to that of Figure 2. Alternately moving the wire up and down through the magnetic field causes the polarity of the induced voltage to change. The polarity of the induced voltage will swing back and forth.**

4. **wire; magnetic field**

5. **(b) results in no induced voltage. — If the field and wire are moving together, the field is not cutting the wire. Therefore, there is no induced voltage.**

6. **True**

7. **The 2-inch wire. — The greater the length of wire cut by a magnetic field, the greater the voltage induced between its ends.**

8. **The rate of cutting lines of force and the amount of wire being cut determine the amplitude of the induced voltage. The rate of cutting depends on both the speed of movement and the strength of the field.**

9. **(b) decrease. — With no field strength there are no lines to cut and there is no induced voltage.**

10. **(b) less output. — Line A is at right angles to the magnetic field. A wire moving along this line has a greater induced voltage than one moving at the same speed along line B.**

11. **(b) almost no voltage induced in it. — For a voltage to be induced in a wire, the wire must cut or be cut by a magnetic field.**

PRACTICE EXERCISE SOLUTIONS (Continued)

12. None — The wire must cut or be cut by a magnetic field for a voltage to be induced in it. Either the wire or the magnetic field must be moving.

13. True

14. Two permanent magnets can be used. They would be placed so that the north pole of one magnet is near the south pole of the other, as shown in Figure 5A. If a single magnet were bent so that its ends were opposite each other, this would serve the same purpose as two separate magnets.

15. To produce an alternating voltage.

16. True

17. (b) Figure 5B. — At this point the loop is cutting the greatest number of magnetic lines.

18. Across the armature. Through the use of slip rings, the two ends of the armature circuit become available for output connections.

19. The loop is cutting the greatest number of magnetic lines when it moves through positions B and D.

20. False — For all practical purposes, the maximum and minimum output values will occur at the same positions. However, the actual value of output at these points may change somewhat.

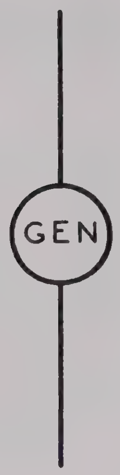
21. Position 2. — The dot on the graph for position 2 is farther from the zero line than the dot for position 5. The greater the distance from the zero line, the greater the induced voltage.

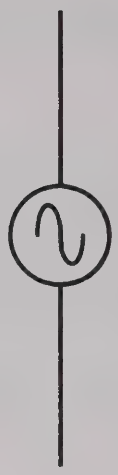
22. (b) negative with respect to wire B. — The wire closest to the north pole of the magnet is positive with respect to the other wire. Thus, wire B is positive with respect to wire A in this position. We can also say that wire A is negative with respect to wire B as the loop passes through this position.

23. False — Because power stations use rotating alternators, you should expect the waveform to have the shape of a sinusoidal curve.

PRACTICE EXERCISE SOLUTIONS (Continued)

24.





25. True — If the generator produces a sinusoidal voltage, the current through its resistive load will also have a sinusoidal waveform.

26. False — The sine curve has curving sides. The sides are mirror images of each other.

27. alternations

28. (b) a cycle. — This curve contains all of the points of a cycle without repeating itself.

29. 51 volts.

$$\begin{aligned}\text{peak-to-peak} &= 2 \times \text{peak}\\ &= 2 \times 25.5\\ &= 51 \text{ volts.}\end{aligned}$$

30. 21.4 volts.

$$\begin{aligned}\text{peak} &= \text{peak-to-peak}/2\\ &= \frac{42.8}{2}\\ &= 21.4 \text{ volts.}\end{aligned}$$

PRACTICE EXERCISE SOLUTIONS (Continued)

31. about 18.03 volts.

$$\begin{aligned} \text{rms} &= .707 \times \text{peak} \\ &= .707 \times 25.5 \\ &= 18.0285 \text{ volts.} \end{aligned}$$

32. About 169.68 volts peak and 339.36 volts peak-to-peak.

$$\begin{aligned} \text{peak} &= 1.414 \times \text{rms} \\ &= 1.414 \times 120 \\ &= 169.68 \text{ volts.} \end{aligned}$$

$$\begin{aligned} \text{peak-to-peak} &= 2 \times \text{peak} \\ &= 2 \times 169.68 \\ &= 339.36 \text{ volts.} \end{aligned}$$

33. (a) increase.

34. (a) rise to 120 Hz. — Doubling the speed doubles the output frequency.

35. doubles

36. (c) dc to ac.

37. False — The output of an inverter is ac. A battery must be charged with dc.

38. An oscillator.

39. AC voltage can easily be increased or decreased in amplitude. AC signals can be radiated through space.

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1031 A&B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1031B

1. D - A FACTOR WHICH DOES NOT AFFECT THE OUTPUT VOLTAGE OF AN ALTERNATOR IS -- THE SIZE OF THE SLIP RINGS.
The factors which affect the output voltage are the length of the conductor, the angle of cutting, the field strength and the speed of cutting.

2. B - IN FIGURE 6, MAXIMUM VOLTAGE IS INDUCED WHEN THE LOOP IS -- PASSING THROUGH POSITION 3.
Maximum induced voltage is induced at positions 3 and 9.

3. D - THE GRAPH OF FIGURE 6 SHOWS -- A SINE CURVE.
Figure 6 shows two complete alternations of a complete sine curve or wave.

4. D - A CYCLE IS MADE UP OF TWO PARTS CALLED -- ALTERNATIONS.
During each alternation the voltage or current increases from zero to maximum and back to zero again.

5. B - DURING ONE CYCLE, AS SHOWN IN FIGURE 10, PEAK VOLTAGE OCCURS -- TWICE.
The peak occurs halfway through each alternation.

6. A - THE PEAK-TO-PEAK VALUE OF A SINUSOIDAL AC VOLTAGE RATED AT 120 VOLTS RMS IS -- 339.36 VOLTS.
The peak value of 120 volts rms is

$$\begin{aligned}\text{peak} &= 1.414 \times \text{rms}\\ &= 1.414 \times 120 = 169.68 \text{ volts.}\end{aligned}$$

The peak-to-peak value is twice the peak value. Thus,

$$\begin{aligned}\text{peak-to-peak} &= 2 \times \text{peak}\\ &= 2 \times 169.68 = 339.36 \text{ volts.}\end{aligned}$$

7. A - TO FIND THE EFFECTIVE (RMS) VALUE OF A SINE CURVE, YOU MULTIPLY THE PEAK VALUE BY -- .707.
The rms value is equal to .707 × peak; while the average value is equal to .637 × peak.

8. C - THE NUMBER OF CYCLES THAT OCCURS IN A SECOND IS CALLED -- THE FREQUENCY.
Frequency is measured in Hertz. One Hertz is equal to one cycle per second.

9. C - INCREASING THE ROTATIONAL SPEED OF AN ALTERNATOR WILL -- INCREASE THE FREQUENCY.
Increasing the rotational speed will also increase the output voltage.

10. A - UNLESS OTHERWISE STATED, AC METERS READ -- EFFECTIVE (RMS) VALUES.
DC meters read the average value.

1031A

All explanations are the same as for 1031B except for those given below.

2. B - IN FIGURE 5, MAXIMUM VOLTAGE IS INDUCED WHEN THE LOOP IS -- PASSING THROUGH POSITION 3.
Maximum induced voltage is induced at positions 3 and 9.

3. D - THE GRAPH OF FIGURE 5 SHOWS -- A SINE CURVE.
Figure 5 shows two complete alternations of a complete sine curve or wave.

5. B - DURING ONE CYCLE, AS SHOWN IN FIGURE 9, PEAK VOLTAGE OCCURS -- TWICE.
The peak occurs halfway through each alternation.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1031B

Example: The ice block home of an Eskimo is called
A ☐
B ■
C ☐
D ☐
A. a tent. B. an igloo. C. a ranch. D. a cave.

1. A ☐ B ☐ C ☐ D ☒
A factor which does NOT affect the output voltage of an alternator is
(A) the speed of the loop. (B) the number of turns on the loop. (C) the strength of the magnetic field. (D) the size of the slip rings.

2. A ☐ B ☒ C ☐ D ☐
In Figure 6, maximum voltage is induced when the loop is
(A) stationary. (B) passing through position 3. (C) passing through position 1. (D) passing through position 0.

3. A ☐ B ☐ C ☐ D ☒
The graph of Figure 6 shows
(A) half of a cycle. (B) a square wave. (C) a rectangular wave. (D) a sine curve.

4. A ☐ B ☐ C ☐ D ☒
A cycle is made up of two parts called
(A) peak voltages. (B) loops. (C) frequencies. (D) alternations.

5. A ☐ B ☒ C ☐ D ☐
During one cycle, as shown in Figure 10, PEAK voltage occurs
(A) five times. (B) twice. (C) once. (D) four times.

6. A ☒ B ☐ C ☐ D ☐
The PEAK-TO-PEAK value of a sinusoidal ac voltage rated at 120 volts rms is
(A) 339.36 volts. (B) 125.76 volts. (C) 169.68 volts. (D) 303.21 volts.

7. A ☒ B ☐ C ☐ D ☐
To find the EFFECTIVE (rms) value of a sine curve, you multiply the peak value by
(A) .707 (B) .637 (C) .5 (D) 2

8. A ☐ B ☐ C ☒ D ☐
The number of cycles that occurs in a second is called
(A) an alternation. (B) the sine curve. (C) the frequency. (D) an alternating current.

9. A ☐ B ☐ C ☒ D ☐
Increasing the rotational speed of an alternator will
(A) reduce the output voltage. (B) reduce the alternating current in the loop. (C) increase the frequency. (D) decrease the frequency.

10. A ☒ B ☐ C ☐ D ☐
Unless otherwise stated, ac meters read
(A) effective (rms) values. (B) average values. (C) peak values. (D) 3.1416 × peak values.

EXPERIMENT 3

ELECTROMAGNETIC INDUCTION AND AC

PARTS NEEDED

1 - Design Console
1 - Multimeter and Test Leads
1 - Electromagnetic Coil
2 - Test Prod Spring Adapters
1 - Permanent Magnet
- Modular Connectors
- Hookup Wire

OBJECTIVE

The purpose of the experiment is to demonstrate the concept of electromagnetic induction and investigate the concepts of RMS, peak, peak-to-peak, and average voltages.

PART 1

PROCEDURE

INDUCTION

1. Connect the leads of the coil used in the electromagnet experiment to two modular connectors. Connect the multimeter to the connectors, so the meter is across the coil. Place the meter on the lowest current range.

2. While inserting the permanent magnet into the center of the coil, observe the action of the meter. Depending on which pole is inserted and how the coil is connected to the meter, the pointer of the meter will either deflect up scale or off scale to the left.

3. Remove the permanent magnet from the coil and observe the action of the meter. The pointer will deflect opposite to the deflection in Step 2.

4. Insert the permanent magnet slowly into the coil. Orientate the magnet so you obtain deflection to the left when the permanent magnet is inserted. Slowly pull the magnet out of the coil, and note the maximum deflection of the meter. Record your result below.

____________________ µA

5. Without changing the orientation of the permanent magnet, reinsert it into the coil, and then quickly remove it. Record the current value below.

____________________ µA

The measurement obtained in Step 4 should be less than the measurement of Step 5. The faster the rate of cutting, the higher the induced current.

6. While holding the permanent magnet stationary, move the coil so the permanent magnet is inserted into the coil. The reaction should be the same as in Step 2. Removing the coil should produce deflection in the opposite direction. Induction will take place when the magnetic field is moved or when the coil is moved.

CONCLUSION

This experiment illustrates that induction takes place if a coil is moved in a magnetic field. The amount of induction depends, in part, on the speed of cutting.

PART 2

PROCEDURE

AC

1. Turn the design console on/off switch to the on position and measure the ac voltage between terminals 2 and 10 of the transformer. Record your measurement below.

________________volts ac

Turn the design console on/off switch to the off position.

2. Using the voltage measured, calculate the peak value, the peak-to-peak value, and the average value. Remember, the meter will always read an RMS value.

Your calculations should be similar to those below where the rated value of the winding is used:

$$E_p = 1.414\, E_{rms} = (1.414)(6.3 \text{ volts}) = 8.91\text{V}$$

$$E_{p-p} = 2E_p = 2(8.9\text{V}) = 17.8\text{V}$$

$$E_{ave} = .637\, E_p = 5.67 \text{ volts}$$

CONCLUSION

In this experiment we have measured one voltage. With various conversion factors we have converted the measured value to some other value. All of the voltages, however, represent the same sinewave but four different ways of measuring the sinewave.

NOTES

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9502-3A
EXAMINATION CHECK SHEET

1. A - IF A PERMANENT MAGNET IS INSERTED INTO THE CENTER OF A COIL AND REMOVED, -- A VOLTAGE WILL BE INDUCED INTO THE COIL.
The law of electromagnetic induction indicates that a voltage is induced if a wire cuts a magnetic field.

2. D - WHICH OF THE FOLLOWING WILL CAUSE A GREATER INDUCED VOLTAGE? -- ALL OF THE ABOVE.
All of these factors will increase the induced voltage.

3. D - WHAT IS THE PEAK-TO-PEAK VOLTAGE, IF THE PEAK VOLTAGE IS 10 VOLTS? -- 20 VOLTS.

$$E_{peak\text{-}to\text{-}peak} = 2\,E_{peak}$$
$$E_{peak\text{-}to\text{-}peak} = 2\,(10 \text{ volts})$$
$$E_{peak\text{-}to\text{-}peak} = 20 \text{ volts}$$

4. A - WHAT IS THE PEAK VOLTAGE IF THE RMS VOLTAGE IS 60 VOLTS? -- 84.84 VOLTS.

$$\begin{aligned} E_{peak} &= 1.414\,(E_{RMS}) \\ &= (1.414)(60) \\ &= 84.84 \text{ volts.} \end{aligned}$$

5. A - WHAT FORM OF VOLTAGE DOES THE MULTIMETER SHOW? -- RMS.
Normally, an ac voltmeter will read the RMS voltage in a circuit.

INDUCTORS AND TRANSFORMERS

1034

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Communications receivers, like the one shown, include both air and iron core inductors and transformers. The iron core inductors and transformers are used at low frequencies. Air core inductors and transformers are used at high frequencies.

Courtesy Collins Radio Company

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> *A person should never be ashamed of possessing but little knowledge. But a person should be ashamed if he fails to add to his knowledge whenever he can and especially so when he fails to make use of it for himself and his fellow men.*
>
> *—Arthur Brisbane*

INDUCTORS AND TRANSFORMERS

Regardless of its size or use, practically every type of electronic equipment uses inductors and/or transformers. Many types of equipment have a transformer in the power supply, although this isn't the only place where transformers are useful.

Whenever one circuit supplies voltage and current to another, if this combination isn't correct for best operation, a transformer can be inserted between the two circuits. The use of a transformer permits the voltage and the current values to be changed to the correct values for proper circuit operation. That is, when the voltage is too low, the transformer increases the voltage and reduces the current, or where a large current is needed, the transformer increases the current and reduces the voltage.

For this action, the transformer makes use of several important factors. One of these is that a voltage can be induced into a wire or coil whenever the wire or coil either cuts or is cut by a magnetic field. In a transformer, however, the coil remains stationary while the magnetic field "moves" (expands and contracts). The second important factor used in transformers is that an alternating current produces a moving magnetic field.

SELF-INDUCTION IN A STRAIGHT WIRE

Electron flow through a wire produces a magnetic field. Let's consider a direct current passing through a wire, shown as a cross section in Figure 1. As long as the electric circuit is not complete, Figure 1A shows no magnetic field around the wire. However, the instant the circuit is completed, a current starts and the conditions in Figure 1B exist. We see that the magnetic field has just started to build up, because all the magnetic lines are still inside the wire, having started from its center.

An instant later, as shown in Figure 1C, the field is building up and there are more magnetic lines, some of which have expanded around the outside of the wire. Each of these lines started at the center and cut through all or part of the wire to reach its present position. In Figure 1D, the current has reached its normal value and the magnetic field has still more lines, most of which have cut through the wire.

If the electron flow in the wire is toward you, or "out" from the page, by the Left Hand Current Rule, the magnetic lines will be around it in a clockwise direction.

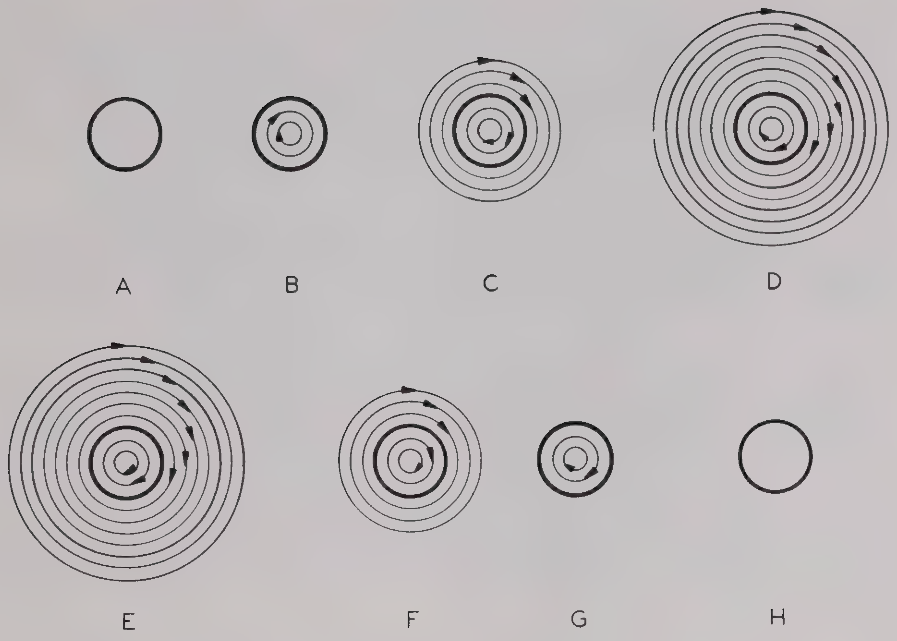


Figure 1

Figure 2A is the cross section shown in Figure 1A with several additions. The outer circle is the entire solid wire, while the small inner circles are drawn, for purposes of our explanation, to represent the solid wire as being made up of many smaller wires or strands which are labelled A, B, C, etc. Electrons are flowing in each of these strands in the same direction as shown for the wire in Figure 1A. Although they are part of one solid wire insofar as action is concerned, each of these strands can be considered as separate physical wires; therefore, A and B are drawn as separated in Figure 2B. Since A and B have electrons flowing through them, each has a magnetic field around it. For simplicity, the field is shown around A only.

This magnetic field is shown in a clockwise direction as it expands from the strand, just as for Figure 1D. As the magnetic field of A passes outside of strand A, it nears strand B. Since the magnetic field of A resists being broken, it bends itself around strand B as shown by the dashed lines, but finally this expanding field cuts strand B and induces a voltage in it. Using the dashed lines as the magnetic field around strand B with the Left Hand Current Rule, the voltage induced in strand B then has a polarity that attempts to force electrons to flow into the page. This is opposite to the source voltage which is causing electron flow out of the page in strand A.

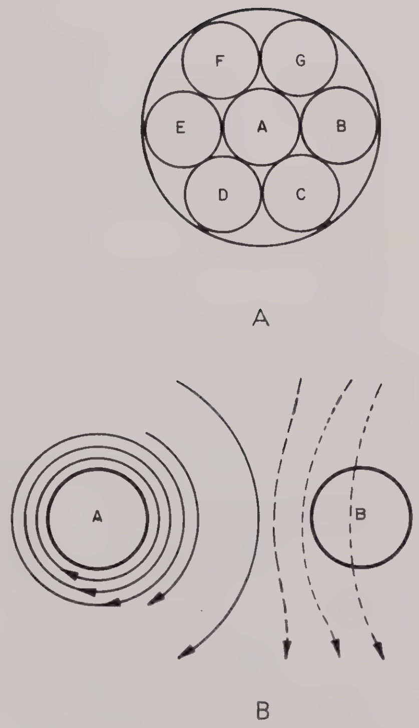


Figure 2

A similar, opposing current is generated in strand A by the expanding field of strand B. Since the voltages in each strand oppose each other, the effective voltage in each of them is the difference between the original supply voltage and the induced voltage. Now, by recombining all the strands as one wire, the voltage induced in the wire by the expanding field opposes the applied voltage so that the resulting voltage is lower. There is also less current in the circuit.

The induced voltage is called a **COUNTER ELECTROMOTIVE FORCE (CEMF)** or counter emf, because it opposes the voltage causing the action.

Inducing a voltage into the conductor is called **SELF-INDUCTION**, and *like all forms of induction, it occurs only while the magnetic field is changing.* Figure 1D shows the full magnetic field. Since no further change occurs (current is maximum), there is no further induction, and the counter emf dies out. Although this complete action takes place very rapidly (in a small fraction of a second), the self-induction does prevent the current from rising instantaneously to its full value.

In Figure 1E, the conditions are identical to Figure 1D; however, we now will examine the action from the instant the circuit is opened. As the current dies out, the magnetic field collapses as shown in Figures 1F, 1G and 1H, which is just opposite to the way it built up in Figures 1A, 1B and 1C. Here again, there is self-induction, but since the magnetic lines are now collapsing, the direction of the induced voltage will be opposite to that which it was while the field was building up. The self-induction, which had opposed the increase of electron flow before, now has reversed its direction in an attempt to maintain the original current for a brief instant.

SELF-INDUCTION IN A COIL

Self-induction in a coil of wire is much greater than in a straight wire of the same length, because the magnetic field around each turn cuts not only the turn that sets it up, but also the turns close to it. To illustrate this action, a coil of wire is shown partially cut away in Figure 3. Using the left hand coil rule, the magnetic field will have the direction shown. Note that the magnetic lines set up around the first turn cut the next turn, and so on.

As this overlapping of magnetic lines occurs between all of the turns, the induced CEMF will be much greater than in a straight wire. The actual amount of self-induction in a coil depends on the ampere-turns and the reluctance of the magnetic circuit. That is, the stronger the magnetic field, the greater the self-induction and the greater the CEMF.

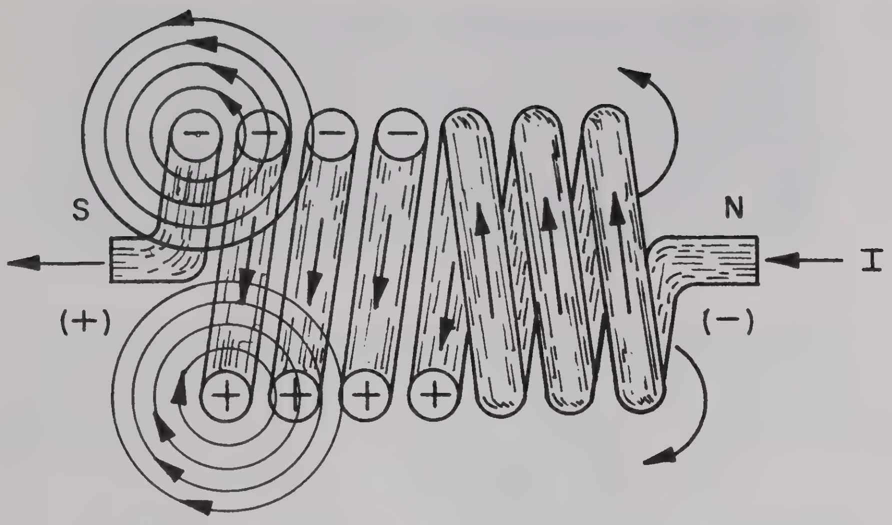


Figure 3

The effects of self-induction are summarized by the following statements:

1. Whenever a circuit current increases, the induced counter emf opposes the change of current and prevents it from rising instantly to its steady value.

2. Whenever a circuit current decreases, the induced emf is in a direction to oppose the change and tends to maintain the current.

Notice particularly that induction occurs only while the current is changing, and the counter emf is always in a direction to oppose the change of current level. With a uniform or steady current, there is no induction, and therefore, no counter emf.

HOW INDUCTANCE CAN BE VARIED

When there is a variation of current in a circuit, the magnetic flux also varies, expanding as the current increases and contracting as the current decreases. In moving, the magnetic lines of force cut any conductor which is within their range and induce a voltage that is always in such a direction as to oppose the current change. The ability to produce a voltage by electromagnetic induction when the current changes is a property possessed by a circuit because of its physical arrangement and is known as **INDUCTANCE**. A conductor has inductance whether or not there is current in it.

The antenna for the AM tuner portion of the above unit consists of a coil of wire wound on a powdered iron core. A powdered iron core increases inductance without the disadvantage of a solid iron core.
Courtesy McIntosh Laboratory, Inc.

The inductance of a circuit depends on the number of magnetic lines that cut the conductor for each ampere change in current. Anything that increases the number of flux lines cutting the conductor for each ampere change in current increases the inductance. A conductor wound into a coil, as shown in Figure 3, has a greater inductance than a straight wire. This is because the flux developed by one turn of wire in the coil also cuts practically every other turn as it expands or contracts. As a result of this additive action, the inductance of a coil is proportional to the number of turns squared. For the same reason, an iron core placed within the coil increases the inductance, because the lower reluctance of the magnetic circuit permits a greater number of flux lines, and therefore, more lines cut the conductor as the current changes. Since a coil of wire possesses the property of inductance, it is called an **INDUCTOR (L)**.

Induction is the result of electromagnetic action in a circuit containing inductance, and as a general definition:

SELF-INDUCTANCE IS THE ABILITY OF A CIRCUIT TO PRODUCE A VOLTAGE WITHIN ITSELF BY INDUCTION WHEN THE CURRENT IN IT CHANGES.

Do not confuse self-induction with self-inductance. Self-induction is the ACT or process of inducing a voltage in the wire or coil, while self-inductance is the ABILITY to induce the voltage.

INDUCTANCE UNITS

As for all other electric properties, there is a unit of measurement for inductance. It is the **HENRY (H)**, named for the American Physicist Joseph Henry (1797-1878) who, in 1831, discovered the voltage caused by self-induction. By definition,

---

THE HENRY IS THE AMOUNT OF INDUCTANCE WHICH INDUCES A COUNTER EMF OF ONE VOLT WHEN THE CURRENT IS CHANGING AT THE RATE OF ONE AMPERE PER SECOND.

The henry is a large unit. Consequently, for many practical applications, two smaller units are employed. One is the millihenry (mH), equal to one one-thousandth ($\frac{1}{1,000}$) of a henry; and the other is the microhenry (μH), equal to one one-millionth ($\frac{1}{1,000,000}$) of a henry.

The schematic symbol for an inductor is shown in Figure 4. This symbol remains the same regardless of the type of winding or the number of turns involved. However, when an iron core is used, it is frequently indicated by adding parallel lines, as shown in Figure 5. The letter "L" along with subscripts 1, 2, 3, 4, etc., are used on schematic diagrams of circuits to identify inductors.

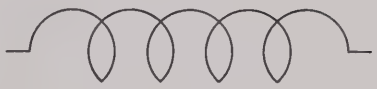


Figure 4

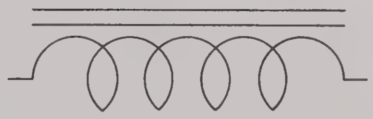


Figure 5

ENERGY STORED IN A MAGNETIC FIELD

Because magnetic lines of force tend to remain as short as possible, some additional force is required to cause a large magnetic field to develop. In an electric circuit, the current-carrying conductors develop magnetic fields because they are connected to a source of electromotive force. The energy supplied by this emf source causes the magnetic field to expand when the level of current is increasing. This expansion is actually a transformation from electric energy to magnetic energy. Because the energy is only changed in form and not dissipated, it may be considered as being stored in the magnetic field.

This energy storing could be compared to winding up the rubber band motor of a model airplane. The mechanical energy of turning the propeller is stored in the twisted rubber band which builds up an opposing (counter) force as the band is wound tighter This is similar to the buildup of the counter emf of the inductance. When the winding is completed, an amount of energy is stored in the rubber band; similarly, when the current has achieved its maximum value, the magnetic field is at its maximum strength.

Releasing the propeller enables the twisted rubber band to unwind and it drives the propeller until the stored energy is all used up. Opening the electrical circuit causes current to rapidly drop to zero and the collapsing magnetic field returns the stored energy to the circuit as an induced voltage that tries to maintain the current.

MUTUAL INDUCTION

A voltage can be induced in a wire or coil by a change of current in an adjacent wire or coil. This electromagnetic induction, due to the moving flux caused by one conductor cutting the other conductors, is called

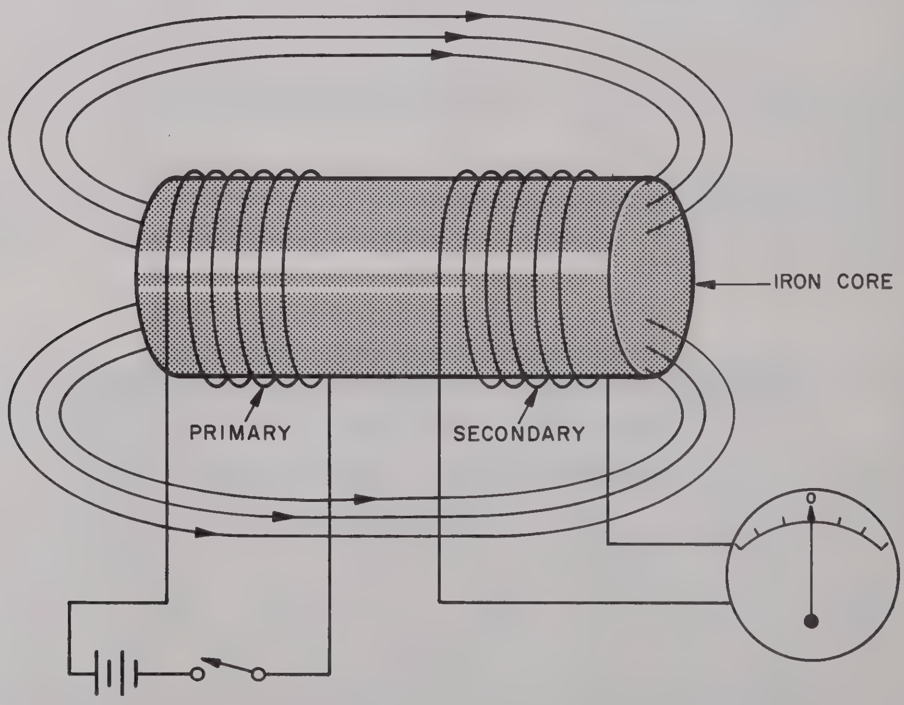


Figure 6

The following Practice Exercise questions cover the subjects which you have just studied. They are:

SELF-INDUCTION IN A STRAIGHT WIRE

SELF-INDUCTION IN A COIL

HOW INDUCTANCE CAN BE VARIED

INDUCTANCE UNITS

ENERGY STORED IN A MAGNETIC FIELD

1. How does a transformer differ from a generator?

2. At the instant current is passed through a conductor, the complete magnetic field appears about the conductor. True or False?

3. As a magnetic field builds up around a conductor due to current through the conductor, the expanding lines of force induce a voltage into the same conductor by a process called _________ - __________________.

4. The self-induced voltage in a conductor caused by current through the conductor is called (a) self-induction, (b) counter emf, (c) counter induction.

5. Counter emf remains constant until the applied voltage is removed. True or False?

6. When the magnetic field around a conductor collapses, the self-induced voltage will be opposite to that of the self-induced voltage when the field was expanding. True or False?

7. The inductance of a coil is zero until current is passed through the coil. True or False?

8. What determines the inductance of a circuit?

9. The unit of measurement of inductance is the ____________.

10. .007 henry = ____________ millihenries; 350 microhenries = ____________ millihenry; and 1200 microhenries = ____________ henry.

11. Draw the schematic diagram symbols for (a) an inductor with an iron core, and (b) another inductor without a core.

(a) (b)

12. Magnetic lines of force require no effort to develop a magnetic field. True or False?

13. Winding the rubber band motor of a model airplane stores mechanical energy in a way that is quite comparable to storing energy in a ____________.

MUTUAL INDUCTION. To illustrate the mutual induction between coils, Figure 6 shows two distinct and separate electric circuits, one consisting of the battery and a coil of wire for the electromagnet, while the other circuit is made up of a coil of wire and a meter. Both coils are wound on the same iron core so that the magnetic field set up by one will cut through the other.

The coil connected to the battery or source of electricity is called the **PRIMARY (P)**, because the first action of setting up the magnetic field occurs around this coil. The other coil is called the **SECONDARY (S)**, because the second action, or the induction of a voltage, takes place when the secondary is cut by the magnetic field of the primary.

The primary circuit consists of the primary winding, the battery, and the switch; the secondary circuit consists of the secondary winding and the meter. As long as the switch is open, nothing happens. There is no current in the circuit; therefore, no magnetic lines are set up around the primary. With no magnetic lines, no induction occurs in the secondary.

When the switch is closed, the primary current produces a magnetic field which starts in the iron core and moves outward, as pictured by the arrowed flux lines. During this interval, the magnetic lines cut through the secondary and induce a voltage in it.

Since the primary coil has a fixed resistance, the voltage of the battery can force only a certain current through it. The strength or magnitude of the magnetic field depends on the ampere-turns of the primary. For the short time it takes the magnetic field to build up, the lines will cut through the secondary coil, but when the field reaches its full strength, the lines no longer move out, no longer cut through the secondary, and therefore induce no further voltage. For this reason, the meter pointer swings toward one side, when the switch in the primary circuit is first closed, and then drops back to zero.

When the primary switch is opened, the current drops to zero and the magnetic lines fall back (collapse) toward the iron core, and again cut through the secondary, but in the opposite direction as when the switch was closed. Therefore, the meter pointer deflects momentarily in the opposite direction.

By closing and opening the primary circuit, building up and collapsing the magnetic field, the lines cut through the secondary. If the primary switch is opened and closed rapidly enough to maintain a continuous change of magnetic flux, a potential difference will be induced in the secondary all of the time, but it will be of one polarity when the switch is closed and of the opposite polarity when the switch is opened. Because the direction of the current caused by this induced voltage reverses periodically, it is an alternating current.

An important thing to remember is that there must be motion between the magnetic lines and the secondary. A varying primary current causes a changing magnetic field, and a secondary placed in the field will be cut by the magnetic lines as they move away from and return toward the primary carrying this current.

The effect of mutual induction between two wires is the same as that between two coils. To illustrate this action, the two wires shown in Figure 7 are electrically insulated from each other but are placed fairly close together. In Figure 7A, with no current in wire 1, there is no magnetic field around either wire. But in Figure 7B, with a current in wire 1, a magnetic field extends around it, out beyond wire 2. The only way these lines can extend beyond wire 2 is by cutting through it.

With a steady current in the wire, the magnetic field builds up and spreads out to some certain distance and then remains constant. A voltage is in-

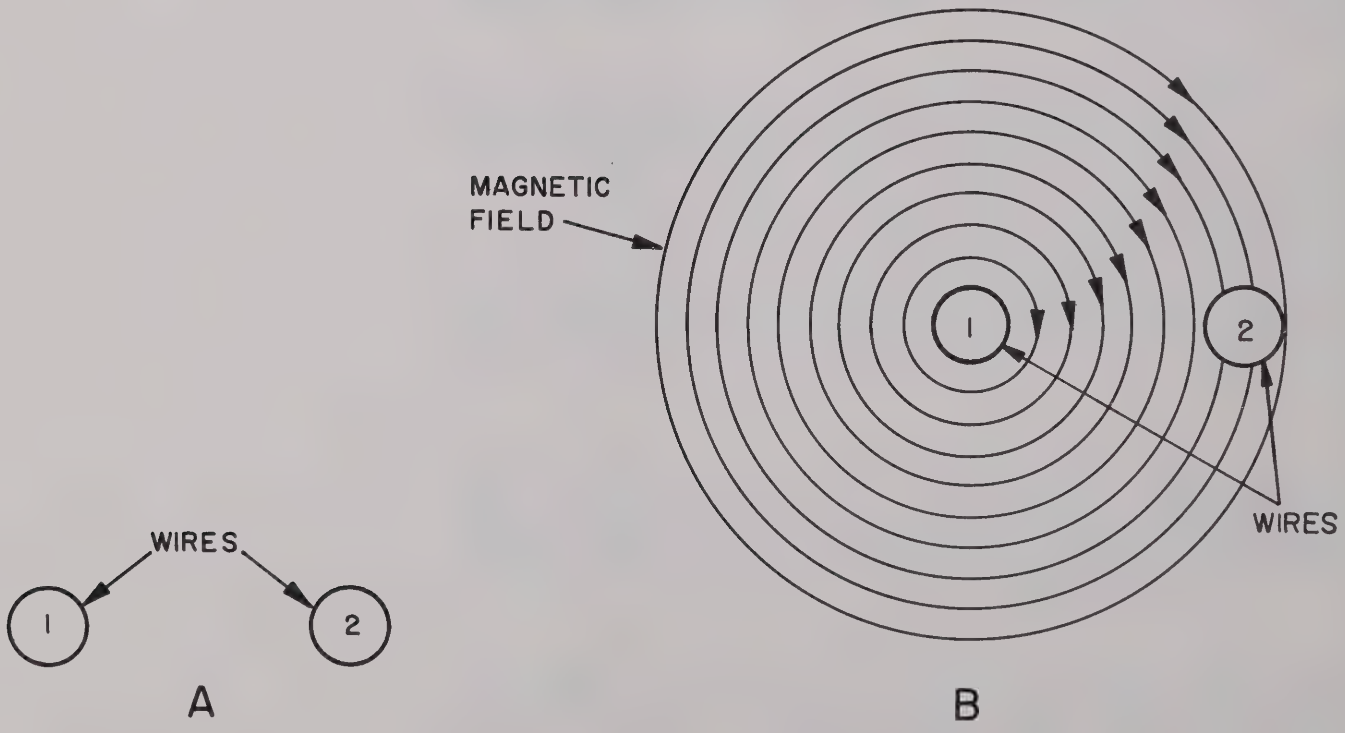


Figure 7

duced in wire 2 while the magnetic field is building up and cutting wire 2, because there is a relative motion between the field and wire 2 while that field is spreading out. However, when the field becomes constant, there is no further motion, and the inductive action ceases.

When the circuit of wire 1 is opened and the current stops, the magnetic field collapses and falls back toward wire 1. The field again cuts through wire 2, but in the opposite direction as when it was spreading out. Again, a voltage is induced in wire 2, but of the opposite polarity.

Just as self-inductance is the ability of a wire to induce a voltage within itself, **MUTUAL INDUCTANCE (M)** is the ability of one conductor or coil to induce a voltage in another. Do not confuse mutual inductance. Mutual induction is the ACT of inducing a voltage in one coil or conductor due to a changing current in another. Mutual inductance is the ABILITY to induce the voltage and this ability exists regardless of the current level in the circuit.

COUPLING AND FLUX LINKAGE

When two coils are placed so that all or part of the magnetic field of one passes or cuts through the conductors of the other, electric energy is transferred from one coil to the other by the mutual induction between them. Because the two circuits are coupled or linked by the changing magnetic lines of force, mutual induction is often referred to as **INDUCTIVE COUPLING**. The closer the coils, the greater the number of lines of force, due to the primary current, that link with the turns of the secondary, and the closer or tighter the coupling is said to be.

The product of the magnetic lines of force and the number of turns in the coil through which they pass is called **FLUX LINKAGE**. In most cases, the position of the coil with respect to a magnetic field determines the actual flux linkage. If the coil is close to a magnetic field so that most of the flux lines thread through the turns, the flux linkage is high, but if the coil is at a distance from the magnetic field, very few lines link with the coil, and the flux linkage is low.

INDUCTORS IN SERIES

In some circuits it becomes necessary to use two or more inductors connected in series. To find the total inductance of such an arrangement, you must first determine if magnetic coupling (mutual inductance) occurs between the inductors.

Series Inductors without Magnetic Coupling

With no magnetic coupling between the inductors connected in series, you can determine the total inductance in the same way that you determined the total resistance of a circuit containing resistors connected in series:

$$L_T = L_1 + L_2 + L_3 + \dots L_N \qquad (1)$$

where: L_T is the total inductance,

L_1, L_2 and L_3 are the inductances, and

L_N means that any number (N) of inductors can be used.

For example, suppose that we have a circuit containing three inductors connected in series. If L_1 is 3 henries, L_2 is 2 henries, and L_3 is .5 henry, the total inductance of this circuit would be:

$$L_T = L_1 + L_2 + L_3$$

$$= 3 \text{ henries} + 2 \text{ henries} + .5 \text{ henry}$$

$$= 5.5 \text{ henries.}$$

Series Inductors with Magnetic Coupling

If two inductors connected in series are arranged so that the magnetic field of one inductor is coupled to the other inductor, the total inductance would be:

$$L_T = L_1 + L_2 \pm 2M \qquad (2)$$

where: L_T is the total inductance,

L_1 and L_2 are self-inductances and

M is the mutual inductance between L_1 and L_2.

The + sign is used with M when the magnetomotive forces of the two inductors are aiding each other. The — sign is used with M when the magnetomotive forces of the two inductors are opposing each other. The factor 2 accounts for the influence of L_1 on L_2 and L_2 on L_1.

For example, suppose that we have a circuit containing two magnetic coupled inductors connected in series. If L_1 is 4 henries, L_2 is 5 henries, and M is .5 henry, and the inductors are connected so that the magnetomotive forces are aiding each other, the total inductance of this circuit would be:

$$L_T = L_1 + L_2 + 2M$$

$$= 4 \text{ henries} + 5 \text{ henries} + 2 \times .5 \text{ henry}$$

$$= 4 \text{ henries} + 5 \text{ henries} + 1 \text{ henry}$$

$$= 10 \text{ henries.}$$

INDUCTORS IN PARALLEL

When the coefficient of coupling between inductors is zero and the inductors are connected in parallel, you determine the total inductance just as you determined the total resistance of resistors in parallel:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots \frac{1}{L_N} \qquad (3)$$

where: $\frac{1}{L_T}$ is the inverse of the total parallel inductance,

L_1, L_2 and L_3 are the inductances, and

L_N means that any number (N) of inductors may be used.

For example, suppose that we have a circuit containing three inductors connected in parallel. If L_1 is 5 henries, L_2 is 10 henries, and L_3 is 10 henries, the total inductance of this circuit would be:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

$$= \frac{1}{5 \text{ henries}} + \frac{1}{10 \text{ henries}} + \frac{1}{10 \text{ henries}}$$

$$= \frac{2}{10 \text{ henries}} + \frac{1}{10 \text{ henries}} + \frac{1}{10 \text{ henries}}$$

$$= \frac{4}{10 \text{ henries}}$$

$$\frac{1}{L_T} = \frac{2}{5 \text{ henries}}$$

To determine the total inductance, simply invert the answer:

$$\frac{L_T}{1} = \frac{5 \text{ henries}}{2}$$

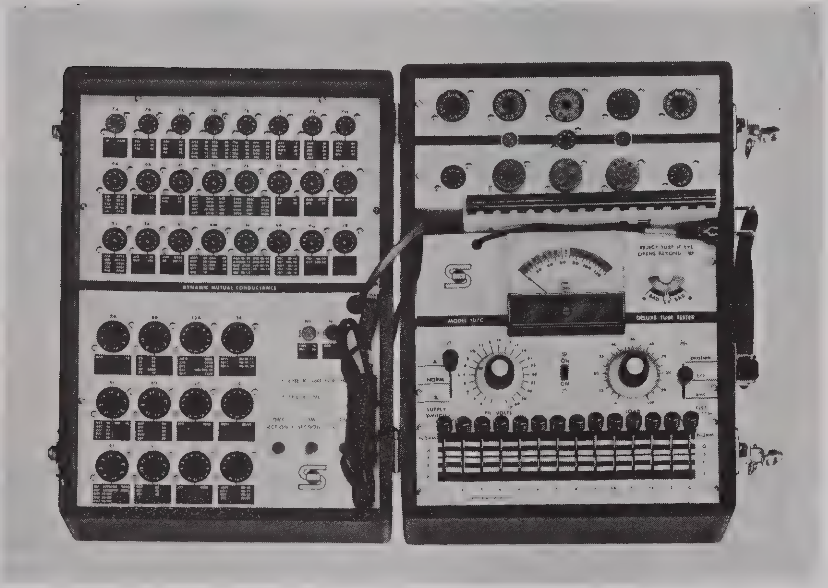
$$L_T = 2.5 \text{ henries.}$$

TRANSFORMER ACTION

The arrangement of two fixed coils wound on a core, as shown in Figure 6, is known as a **TRANSFORMER**. A transformer is an electric device, without mechanically moving parts, for transferring electric energy from one or more circuits to one or more other circuits by electromagnetic induction.

A very important point to remember is that, although a battery is shown, a transformer will not operate with a steady current in the primary. For electromagnetic induction to occur, there must be a changing magnetic field, which is produced when the switch of Figure 6 is closed or opened. For an instant after the closing or opening of the switch, the magnetic field is building up or dying out and a voltage is induced into the secondary. At all other times, the magnetic field is stationary and no induction can occur.

For the transformer to operate continuously, the primary winding must be connected either to an intermittent source of current or to some source of alternating current. An alternating current continuously changes in value and periodically reverses its direction. Therefore, around a primary that is carrying an alternating current, the magnetic field is constantly building up and dying down, first in one direction and then in the other. These changes of the field mean that the magnetic lines continually cut through the secondary and induce a voltage in it.



Tube testers employ a transformer with a number of taps on the secondary to provide the various filament voltages for the tubes under test.
Courtesy SECO Electronics Corp.

TRANSFORMER CORES

Frequently, transformer cores are formed into a square or rectangular "loop" to provide a complete, closed path or circuit for the lines of magnetic flux. A solid block of steel with a square hole in the center has the primary coil wound around one "leg" and the secondary coil wound on the other "leg." Produced by the current in the primary, the flux is carried almost entirely by the core and passes through the secondary winding to induce the desired emf.

In addition to a magnetic circuit, the solid metal core forms a path for electric currents which are induced in it by the flux. To reduce these currents which cause heat loss, practical metal cores are made of a large number of thin sheets called **LAMINATIONS**, as shown in Figure 8. These laminations are tightly bolted together.

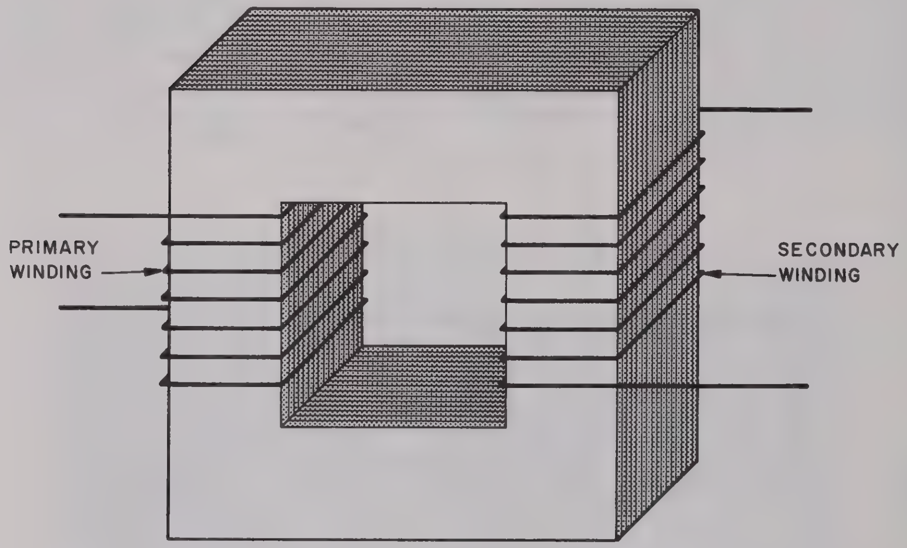


Figure 8

The laminations are cut or stamped from thin sheets of steel which generally range from 6 to 25 thousandths of an inch in thickness. The steel sheets which are used have a scale on their surfaces, and when the core is formed, the scale insulates the laminations from those adjacent; this prevents currents from passing from one lamination to the next. Therefore, loss due to an induced current is reduced to a low value.

To avoid the difficulty of threading the turns of coil wire through the central opening of a solid core similar to the one shown in Figure 8, the laminations are shaped so that two pieces are required to form a rectangle. With this system, the coils can be wound without a core, and after they are completed, the laminations can be placed in their central opening.

One type of lamination, shown in Figure 9A, has an L shape. With the finished coils in their proper position, one L lamination is placed in the center of each coil. Additional laminations are then stacked in the coils to form the completed core, shown in Figure 9B. Usually, one side of the L is longer

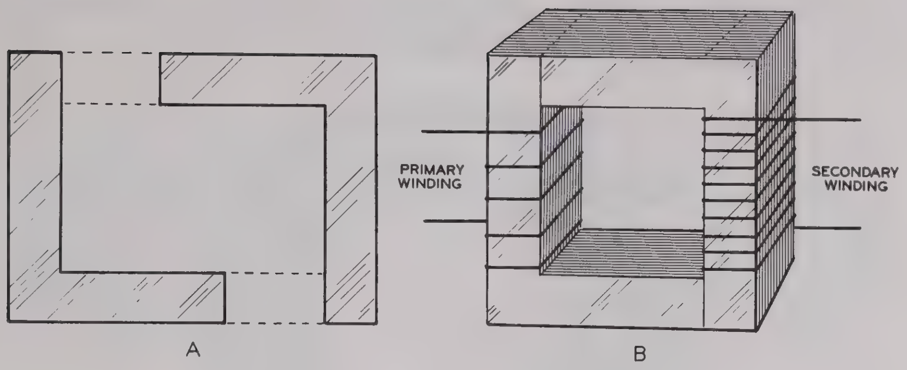


Figure 9

than the other and they are stacked alternately to provide the indicated staggered joint between adjacent rectangles.

Another common transformer core is made of “E” and “I” shaped laminations as shown in Figure 10A. This arrangement forms two rectangles and all of the coils are made to fit on the center bar of the E. As explained for Figure 9, the laminations are stacked in the center opening of the finished coils to form the assembly of Figure 10B.

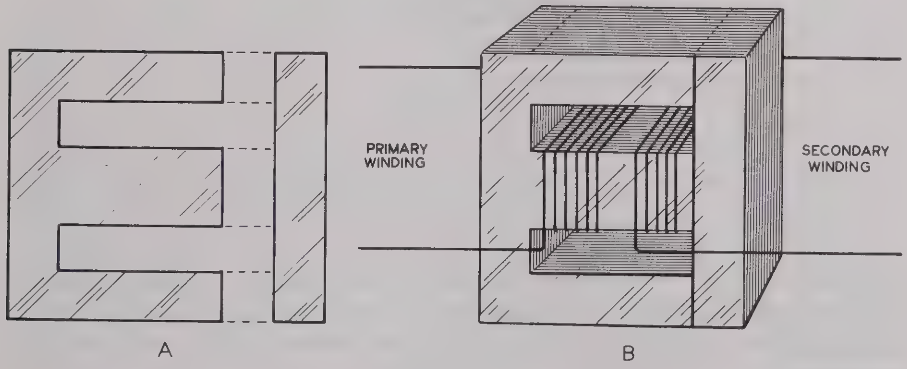


Figure 10

Laminations of this shape can be stacked in either of two ways. First, adjacent “E’s” are inserted from opposite ends of the coil and each layer is completed with an “I.” This forms the staggered joints indicated in Figure 10B. Second, all the E’s can be inserted from the same end of the coils to provide the core illustrated in Figure 11. Then, an equal number of I laminations are placed across the open end of the E's to complete the core.

Figures 9B and 10B are "semi-schematic" insofar as the windings are concerned, in order to show the core construction. The actual arrangement used in a practical transformer is illustrated by the cutaway view in Figure 11. Here, the I stack is removed to show that both windings consist of a relatively large number of turns.

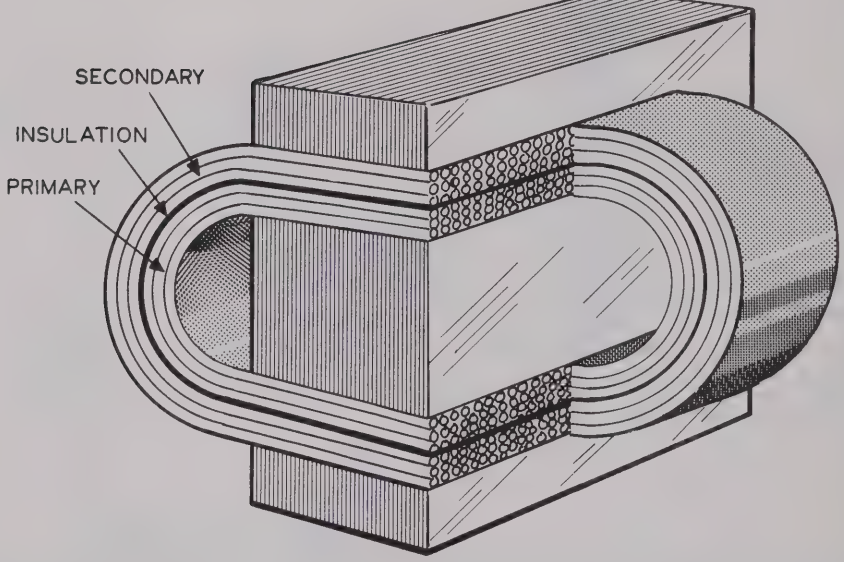


Figure 11

The primary is wound around the entire center leg of the E stack and the secondary is wound around the primary, while a layer of insulation separates the two windings. The wires in the primary and secondary windings are insulated to prevent turn-to-turn shorts. When the windings and core have been assembled, the entire unit is clamped together with bolts extending through the stacks.

The square corner design of the transformers shown in Figures 10 and 11 results in some flux leakage. Figure 12 shows a more efficient core design. This type of core is referred to as a **TOROID** core. The circular shape of the core confines the magnetic field to the core and the inner hole. There is little if any magnetic field external to the core. The primary and secondary windings can either be separate, as shown in Figure 12, or wound on top of one

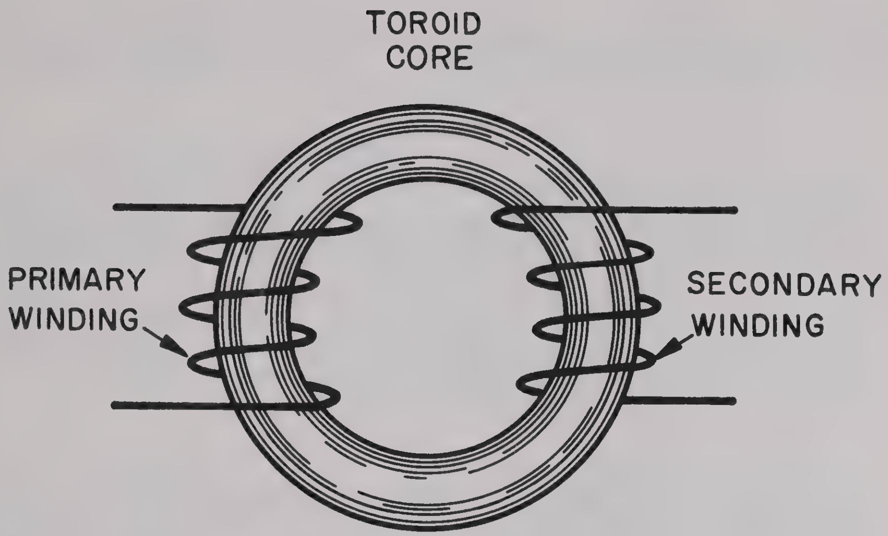


Figure 12

another. Due to the circular shape of the core, special winding machines are used, with a resultant increase in cost over a conventional E-I core.

TRANSFORMER LOSSES

A properly designed transformer is a very efficient device; however, there are certain factors that prevent the transformation of the input voltage and current to the desired output voltage and current with 100% efficiency. These factors are transformer losses, and they are of three general types: (1) copper losses, from the materials used in the transformer windings; (2) core losses, which come principally from the material, size and shape of the transformer core; and (3) stray losses of various kinds.

Copper losses occur in the form of heat which is produced by the currents in the conductors of the transformer windings. Called I^2R losses, they relate to the amount of current in the winding and the resistance of the conductors. These losses are minimized by employing large diameter conductors to reduce the resistance per unit length of the wires. Copper losses are generally about twice as great as core losses in most transformers.

Core losses, also called "iron losses," mainly affect transformers with cores of magnetic material and are of two kinds: hysteresis losses and eddy current losses. **HYSTERESIS** losses are the main type of core loss, comprising about three-fourths of the total. "Hysteresis" describes the tendency of the core material to oppose a change in magnetism.

Each time the magnetizing force produced by the primary of a transformer changes because of the applied ac power, the atoms of the core realign themselves in the direction of the force. The energy to accomplish this realignment of the magnetic atoms comes from the input power and is not transferred to the secondary winding; it is therefore a loss. Because various types of core materials have different magnetizing abilities, the selection of core material is an important factor in reducing core losses.

Another way of considering this is that, whenever the flux density is being increased, the magnetizing force must be a little greater than it would be if hysteresis were not a factor. Also, after the magnetizing force has reduced to zero at the end of an alternation, a certain magnetization remains in the core which can be decreased to zero only by the application of magnetizing force in the opposite direction. During each cycle, a certain percentage of the total energy supplied is used to overcome the hysteresis effect, and this energy is lost as far as the transformer is concerned.

Earlier, we mentioned currents in the solid metal core caused by induction from the magnetic field. This current is actually the **EDDY CURRENT** loss. In iron core transformers, the iron must also be considered as a conductor because it is affected by the magnetic field just as the secondary winding is. Small voltages are induced in the core by the changing magnetic field; these currents cause I^2R losses in the core.

By using a laminated core, the path of the eddy currents is broken up without increasing the reluctance of the magnetic circuit. The laminations lie in the same direction as the flux. Therefore, the insulating surfaces are directly across the path of the eddy currents. The resulting eddy current reduction improves the efficiency of the transformer.

All of these losses make the typical transformer hot when it operates under full load. In fact, the amount of heat the insulation can take without breaking down helps to determine the power limitations of the transformer. Although some transformers operate too hot to hold comfortably, there should be no odor of burning insulation or varnish, or signs of discoloration or smoke. Any one of these conditions would indicate that the transformer is overloaded.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

MUTUAL INDUCTION

COUPLING AND FLUX LINKAGE

INDUCTORS IN SERIES

SERIES INDUCTORS WITHOUT MAGNETIC COUPLING

SERIES INDUCTORS WITH MAGNETIC COUPLING

INDUCTORS IN PARALLEL

TRANSFORMER ACTION

TRANSFORMER CORES

TRANSFORMER LOSSES

14. The action of a voltage being induced in one wire or coil by a change of current in another wire or coil is called (a) primary to secondary induction, (b) mutual induction, (c) mutual inductance.

15. With a maximum, steady, primary current, the magnetic field is at its maximum value in the primary. If the magnetic field has been constant for at least one second, maximum mutual induction is occurring. True or False?

16. What do we call the ability of one circuit to induce a voltage in another circuit?

17. Mutual induction exists in a circuit even when no current flows. True or False?

18. Another name for mutual induction is ________________.

19. How would you calculate the flux linkage in a circuit?

20. What is the total series inductance of a circuit containing three inductors, when L_1 is 5 henries, L_2 is 4 henries, and L_3 is 1 henry and there is no magnetic coupling between the inductors?

21. What is the total series inductance of a circuit containing two inductors, when L_1 is 3 henries, L_2 is 7 henries, the mutual inductance between L_1 and L_2 is 2 henries, and the magnetomotive forces of the two inductors are opposing each other?

22. What is the total parallel inductance of a circuit containing three inductors, when L_1 is 6 henries, L_2 is 3 henries, and L_3 is 2 henries?

23. Why are the two windings of a transformer called the primary and secondary?

24. A transformer will not operate properly with steady direct current applied to the transformer primary. True or False?

25. What is the major purpose of a transformer core?

26. Why is a transformer core usually made of steel laminations?

27. What is an advantage of a transformer with a toroidal coil?

28. Electric currents induced into the core of a transformer are undesirable and should be reduced to a minimum. True or False?

29. Hysteresis losses can be minimized by (a) proper selection of core material, (b) laminating the core, (c) using large diameter conductors for the windings.

STEP-UP AND STEP-DOWN TRANSFORMERS

Not only is a transformer employed to transfer electric energy from one circuit to another, as we mentioned earlier, it also can be used to raise or lower the voltage to meet certain operating requirements. For example, in practically all alternating current power lines, the voltage is "stepped up" at the power station, carried long distances, and then "stepped down" at the place where it is used. Also, in practically all electronic apparatus designed to operate from 110-volt ac lighting circuits, transformers are used to lower the voltage for some circuits and raise it for others.

The induced secondary voltage is affected by four factors: the speed of cutting the lines of force, the angle of cutting, the strength of the flux and the length of the conductor being cut. The speed of cutting cannot be changed in a transformer because it is controlled by the rate at which the magnetic field of the primary builds up and collapses. When the primary circuit is closed and opened, the change in magnetic flux takes place as rapidly as possible. The angle of cutting cannot be changed, since the coils are arranged permanently on the core. Also, the strength of the field can be ruled out because it is determined by the core material and the ampere-turns of the primary coil, which is made up of a specific number of turns and with a certain resistance, so that it carries a definite current.

Only the length factor is left. Suppose that the secondary is wound with twice as many turns as the primary. Then, the same number of magnetic lines, moving at the same speed and cutting at the same angle, but cutting twice the length of wire, produces twice the voltage in the secondary. The reverse also is true. If the secondary is wound with half as many turns as the primary, then the same number of magnetic lines, moving at the same speed and cutting at the same angle, but cutting half the length of wire, produces half the voltage in the secondary.

These two examples illustrate the definite relationship between the number of turns and the voltage of each winding. As a general rule, this relationship may be stated as:

IN A TRANSFORMER, THE SECONDARY VOLTAGE DIVIDED BY THAT OF THE PRIMARY IS THE SAME AS THE NUMBER OF TURNS IN THE SECONDARY DIVIDED BY THOSE IN THE PRIMARY.

That is, in equation form:

$$\frac{E_S}{E_P} = \frac{N_S}{N_P} \tag{4}$$

where: E_S and E_P are the secondary and primary voltages, and N_S and N_P are the secondary and primary turns.

If the primary turns and voltages are known and it is desired to determine the number of turns required for a given secondary voltage, the expression may be rewritten:

$$N_S = N_P \frac{E_S}{E_P} \tag{4a}$$

and the known values submitted for the letters. In words, Equation 4a says: "*Multiply the secondary voltage by the number of turns in the primary and divide this number by the voltage of the primary to get the number of turns in the secondary.*" To illustrate the use of the equation, assume that the primary of Figure 6 has 30 turns and operates at 3 volts. How many secondary turns are required to produce 300 volts?

N_S = 30 times 300 divided by 3; or 3000 turns.

The other factors in Equation 4 can be found by rearranging the expression as shown below:

$$N_P = N_S \frac{E_P}{E_S} \tag{4b}$$

$$E_P = E_S \frac{N_P}{N_S} \tag{4c}$$

$$E_S = E_P \frac{N_S}{N_P} \tag{4d}$$

The ratio between the number of turns in the primary and the secondary is called the TURNS RATIO. Written as an expression:

$$N = \frac{N_S}{N_P} \text{ or } N = \frac{N_P}{N_S} \tag{5}$$

where: N is the turns ratio.

Use the form which gives an answer of 1 or greater.

Since the primary and secondary voltages and turns are related, the turns ratio may also be expressed in terms of the primary and secondary voltage. Use the form of Equation 5a which results in an answer of 1 or greater:

$$N = \frac{E_S}{E_P} \text{ or } N = \frac{E_P}{E_S} \tag{5a}$$

In expressing turns ratios, it is convenient to divide the larger number by the smaller and indicate whether the transformer is a step-up or step-down transformer. For example, if the primary has 100 turns and the secondary has 5 turns, the turns ratio may be given as 100:5 = 20:1 (step-down). This is read as "twenty-to-one step-down." If the primary has 200 turns and the secondary has 1000 turns, the turns ratio may be given as 1000:200 = 5:1 (step-up). This is read as "five-to-one step-up."

Remember that transformers may be used to raise or lower voltage. A transformer with more turns of wire in the secondary than in the primary, as in Figure 9, is known as a **STEP-UP** transformer, since it increases the voltage. One with fewer turns in the secondary than in the primary, as in Figure 10, causes a decrease of voltage, and therefore, it is known as a **STEP-DOWN** transformer.

TRANSFORMER POWER

The mutual induction between the primary and secondary of a transformer makes it possible to transfer electric energy from one circuit to another. In doing so, it is possible to change the value of the induced voltage. However, a transformer cannot increase the total power. If the transformer steps up voltage, the secondary current is correspondingly less than the primary current so that the power (voltage times current) is the same in both windings.

In Figure 13A, with an ac voltage applied across the primary, the induced counter emf holds the current to the small amount necessary to replace the energy lost in the resistance of the wire. A voltage is induced in each turn of the primary and secondary windings, but with no external circuit, there is no secondary current. However, when an external circuit path is provided, the induced secondary voltage causes current in that circuit, as depicted in Figure 13B.

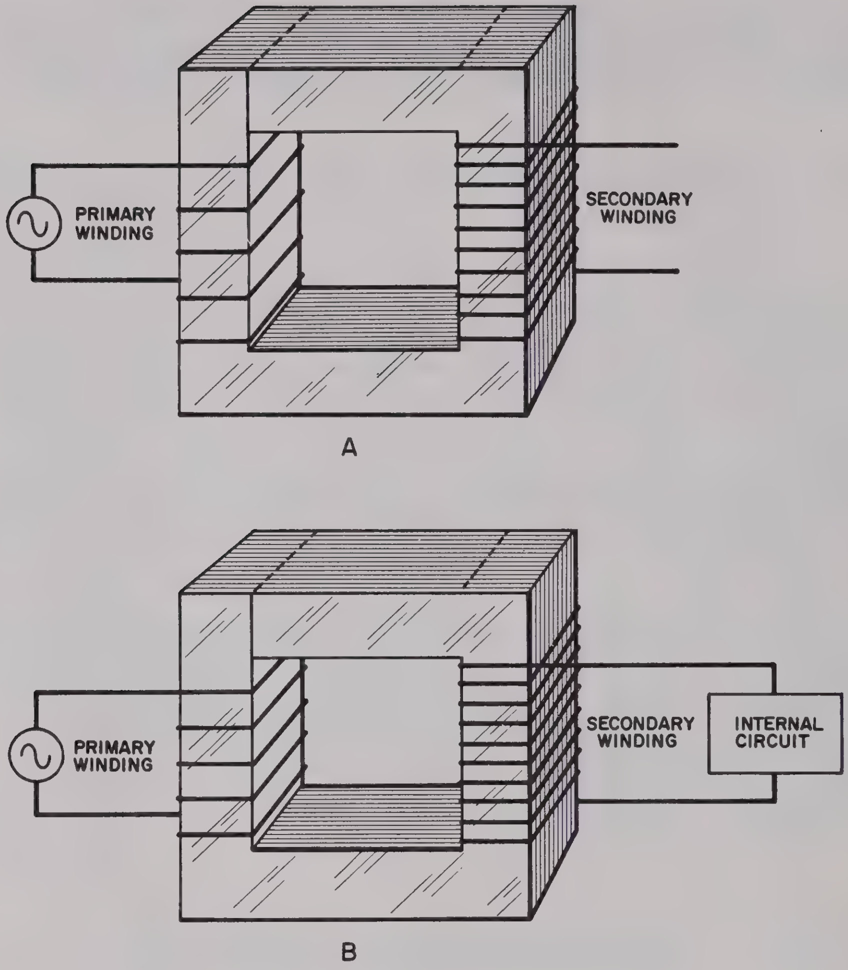


Figure 13

Remember that the current direction in the secondary is opposite to that in the primary. Therefore, the magnetic field set up by the secondary current opposes and weakens the field caused by the primary current. This weakened field induces a lower counter emf and, therefore, the primary current increases.

The higher the secondary current, the greater the weakening of the overall field and the greater the primary current. These actions are so balanced that any power delivered by the secondary causes a corresponding increase of power taken from the source by the primary.

The power in a transformer is measured in watts and is equal to the voltage times the current. Because of losses in the core and those due to resistance of the wire (copper losses) in the primary winding, the power available to the secondary is always slightly less than that in the primary. For most circuits, these losses are a very small part of the total power handled. Therefore, for all practical purposes, the power in each winding is so nearly equal that it can be written in abbreviated form as:

$$E_P I_P = E_S I_S, \tag{6}$$

where: E_P = primary voltage,

I_P = primary current,

E_S = secondary voltage, and

I_S = secondary current.

This means E_P times I_P is the same number of watts as E_S times I_S. These terms can be rearranged to calculate any one value when the other three are known. For example:

$$I_S = I_P \frac{E_P}{E_S} \tag{6a}$$

The transformer of a previous example developed 5 volts in its secondary when a 100-volt source was connected across its primary. Assuming a primary current of 2 amperes, the secondary current is:

$$I_S = \frac{2 \times 100}{5} = \frac{200}{5} = 40 \text{ amperes.}$$

For the primary, the power is:

$$100 \text{ volts} \times 2 \text{ amperes} = 200 \text{ watts.}$$

For the secondary, the power is:

$$5 \text{ volts} \times 40 \text{ amperes} = 200 \text{ watts.}$$

Thus, with no increase in available power, a transformer secondary can provide higher voltage with lower current or lower voltage with higher current than that existing in the primary.

The primary and secondary currents can also be related to the number of turns in the primary and the secondary, as shown below:

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \qquad (7)$$

This expression can also be arranged to find one of the factors when the other three are known. For example, if the number of turns in the primary and secondary are known along with the primary current, the secondary current may be found as shown below:

$$I_S = I_P \frac{N_P}{N_S} \qquad (7a)$$

Similarly, Equation 7 can be rearranged to determine the three other factors:

$$I_P = I_S \frac{N_S}{N_P} \qquad (7b)$$

$$N_P = N_S \frac{I_S}{I_P} \qquad (7c)$$

$$N_S = N_P \frac{I_P}{I_S} \qquad (7d)$$

COUPLING

When two coils are placed so that all or part of the magnetic lines of one coil pass (or cut) through the conductors of the other coil, flux linkage occurs and there is inductive coupling between the inductors. The amount of flux linkage determines the "degree of coupling." For example, if all of the magnetic lines produced by a current in one coil cut across its turns and also cut across all of the turns of another coil, the flux linkage will be the greatest possible. Then a maximum condition of UNITY COUPLING is said to exist.

In actual practice, there is always a certain amount of "flux leakage"; that is, some of the magnetic lines will "leak" off into space without cutting the second coil. Therefore, unity coupling is never achieved, and the degree of coupling is always less than 1.

The degree of coupling and the number of turns on the windings are grouped together and expressed in terms of a property called mutual inductance (M). Mutual inductance, like self-inductance, is measured in henries. In terms of mutual inductance, the secondary voltage is equal to M times the rate of change of primary current. The maximum possible theoretical value of mutual inductance, M_m, obtained when all of the flux lines produced by the primary link the secondary, is shown by the following expression:

$$M_m = \sqrt{L_P L_S} \tag{8}$$

where: M_m is the maximum possible theoretical value of mutual inductance in henries,

L_P is the inductance of the primary in henries, and

L_S is the inductance of the secondary in henries.

In practice, it is impossible for all of the flux lines produced by the primary to link the secondary, and M is always less the $\sqrt{L_P L_S}$. The ratio between M and $\sqrt{L_P L_S}$ is called the **COEFFICIENT OF COUPLING (k)**. In the form of an equation:

$$k = \frac{M}{\sqrt{L_P L_S}} \tag{9}$$

For perfect (unity) coupling, when M is equal to $\sqrt{L_P L_S}$, the coefficient of coupling is equal to 1. Unity coupling is closely approached in iron-core transformers and partly accounts for their high efficiency. Conversely air core transformers, such as those used at radio frequencies, may have coefficients of 0.05 or less.

The flux produced by a winding which does not link the other windings of a transformer is called a LEAKAGE FLUX. Leakage flux may be schematically represented by an inductance in series with the winding. This **LEAKAGE INDUCTANCE** is especially troublesome at high frequencies because it opposes high-frequency currents. Leakage inductance, along with some other factors, determines the upper frequency limit of a transformer (the maximum frequency at which it will satisfactorily operate).

Leakage inductance can be minimized by interleaving the primary and secondary windings in an attempt to make all of the magnetic flux produced by one winding link with the other winding.

SYMBOLS

The symbol for a transformer is given in Figure 14. The loops represent the turns of wire in the coils, the extended lines at each end of the series of loops represent the circuit connections, and the parallel lines in the center represent an iron core. No attempt is made to indicate the number of turns in each winding, although the operating voltages may be indicated as shown.

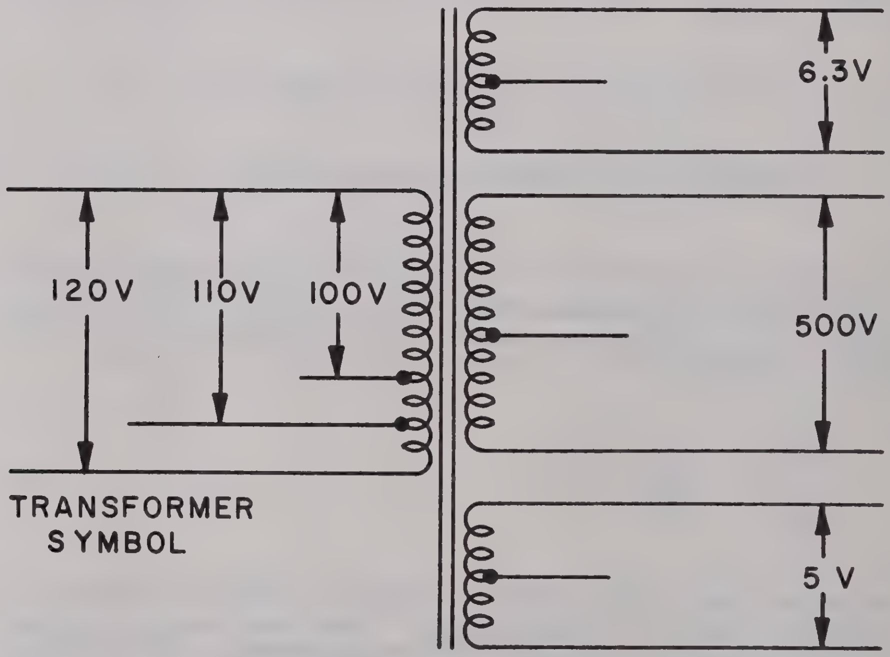


Figure 14

This symbol is that of a common type of "power transformer." The primary operates on the ordinary 110-volt house ac lighting circuit, and is indicated by the coil on the left. Because the house lighting circuit voltages may vary in different locations, the symbol shows that this particular winding is tapped for operation at 100, 110 or 120 volts.

To explain the operation of these taps, suppose that the transformer is designed on the basis of 10 turns per volt. This means a drop of one volt across each 10 turns of the primary, and an induction of one volt for each 10 turns of the secondaries. Under these conditions, that portion of the primary indicated by the "100V" arrow contains 10 × 100, or 1,000 turns.

As the primary and secondary voltages are proportional to the number of turns, the 6.3-volt secondary has 10 X 6.3, or 63 turns, and the 500-volt secondary has 10 × 500, or 5,000 turns.

Now, suppose that the supply voltage rises to 110 volts. Connected across the 1,000-turn primary, the drop will be 1,000 divided by 110 or approximately 9 turns per volt. Under these conditions, the 6.3-volt winding develops 63 divided by 9, or 7 volts, and the 500-volt winding will develop 5,000 divided by 9, or approximately 555 volts.

To prevent this undesirable rise in secondary voltages, the 10 turns per volt factor is reestablished by adding 100 turns to the primary winding between the 100V and 110V taps. With the 110-volt source connected as shown by

The variable transformer shown is actually an autotransformer with an adjustable tap.

Courtesy General Radio Company

the arrow, 110 volts across 1,100 turns provides the normal 10 turns per volt drop and thus produces the normal secondary voltages.

The increased number of primary turns compensates for the increased voltage, the turns ratio of the 500 volts winding is now 5,000 divided by 1,100, or approximately 4.55, and 4.55 times the 110-volt primary is 500.5 volts. Similarly, another 100 turns on the primary will provide proper secondary voltage with a 120-volt supply.

Three secondary windings on the symbol of Figure 14 are shown, each with a middle connection, or "center tap." The upper winding develops 6.3 volts; the center winding, 500 volts; and the lower winding, 5 volts. By a comparatively simple symbol, the circuit arrangements and voltages of a typical power transformer with four windings and 13 external connections are shown. As far as the circuit connections are concerned, the symbol provides complete information.

According to this plan, any inductor or transformer can be represented by an accurate symbol. If no iron core is used, the central parallel lines are omitted. In fact, these parallel lines sometimes are omitted from the diagram where there can be no question that an iron core inductor or transformer is used.

AUTOTRANSFORMERS

An **AUTOTRANSFORMER** is a transformer with a single winding, as shown in Figure 15A. Here, the primary and secondary form a single, tapped winding. Although they are connected together, the primary circuit does not include the secondary, and the secondary circuit does not include the primary.

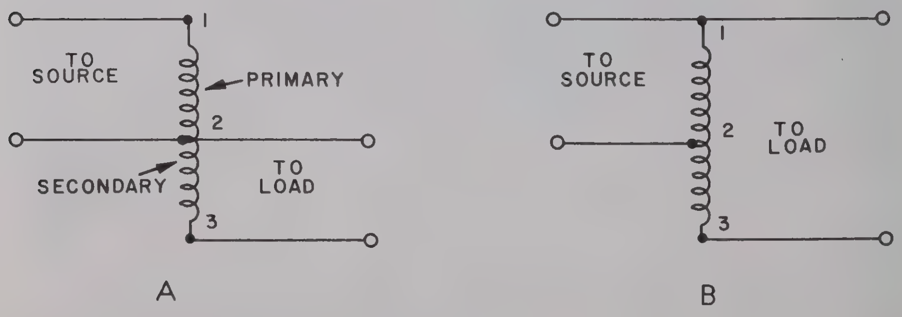


Figure 15

Transformer action is the same as explained for conventional multiple-winding transformers.

Assuming that the primary and secondary windings have an equal number of turns, the secondary voltage equals the primary voltage in Figure 15A. In Figure 15B, the source is connected between terminals 1 and 2 and the load is connected between terminals 1 and 3. Here, half the winding acts as the primary, while the entire winding acts as the secondary. With a turns ratio of 2:1 (step-up), the secondary voltage is twice the primary voltage.

Notice that, in the connection of Figure 15B, the portion of the winding serving as the primary must carry the secondary current as well as the primary current. Autotransformers are usually economical only with turns ratios no higher than about 4:1. For a given power rating, they can be made smaller and more compact than transformers with two windings.

SUMMARY

When the current through a conductor or coil is changed, the changing magnetic field develops a counter electromotive force. This counter emf tends to oppose any change in current. The opposition that a conductor or coil offers to a changing current is called inductance. The basic unit for inductance is the henry.

A transformer employs the property of mutual inductance, which is the ability of one conductor to induce an emf in another nearby conductor. An actual transformer consists of a primary and one or more secondary windings, wound on a common core. A magnetic core material can be used to confine the magnetic lines of force and reduce flux leakage. By choosing the proper number of turns on the primary and secondary windings, a step-up or step-down transformer can be obtained. A step-up transformer provides a higher secondary than primary voltage and vice versa.

A transformer is not a perfect device and some power is lost in the energy transfer from primary to secondary. The energy loss is in the form of flux leakage, copper or I^2R losses in the conductors, hysteresis and eddy currents. The use of large conductors reduces I^2R losses. Good core design reduces flux leakage and hysteresis losses. Eddy currents are reduced by using a laminated core.

The inductor symbol used on many drawings resembles a coil spring; if it has a magnetic core, straight lines are shown adjacent to the coil. A transformer is also illustrated by a similar symbol except that each winding or coil is shown separately. All primary windings are on one side of the core symbol and the secondary windings are on the opposite side.

The ratio of the turns of primary winding to the turns of secondary winding is called the turns ratio. This is the basis for determining how much the primary voltage is stepped up or down in the secondary. The voltage times current product of the primary must equal that of the secondary. A higher voltage in the secondary (from a step-up transformer) is accompanied by a reduced value of current, while a step-down transformer provides a lower voltage and a higher current.

In an autotransformer, the primary and secondary coils form a single tapped winding, but the connections are arranged so that primary circuit portion does not include the secondary. The transformer action is identical to multiple-winding transformers; however, the turns ratio is usually much more limited than with other transformers.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

STEP-UP AND STEP-DOWN TRANSFORMERS

TRANSFORMER POWER

COUPLING

SYMBOLS

AUTOTRANSFORMERS

30. If a transformer with a primary of 100 turns is operating at 20 volts, how many turns must the secondary have to develop 50 volts?

31. For a step-down transformer with a turns ratio of 5 to 1, what is the output voltage if the voltage on the primary is 110 volts?

32. A certain transformer has an output of 330 volts when operated from a 110-volt ac power line. What is the turns ratio?

33. What is the output of a transformer operated from a 110-volt ac power line if the primary has 250 turns and the secondary has 1000 turns?

34. In a transformer, what is the power in the secondary always equal to?

35. A transformer with a primary of 100 turns that operates at 20 volts has a primary current of 5 amps. If the secondary develops 50 volts, what is the value of the secondary current?

36. A certain transformer operated from a 110-volt ac power line has a secondary voltage of 605 volts and a secondary current of 2 amps. Will this arrangement blow a 10-amp fuse in the primary?

37. Unity coupling means (a) a turns ratio of 1 to 1, (b) maximum coupling, (c) a single secondary.

38. **Flux leakage means a leakage of flux lines from primary to secondary through the insulation. True or False?**

39. **In transformer formulas, the letter k represents the (a) coefficient of coupling, (b) energy in the primary, (c) turns ratio, (d) distance between the windings.**

40. **Suppose that a transformer has a primary inductance of 360 microhenries and a secondary inductance of 250 microhenries. If the mutual inductance (M) is 160 microhenries, what is the coefficient of coupling? (a) 1.5 (b) 0.53 (c) 2.0 (d) 1.0**

41. **An autotransformer contains (a) only one winding, (b) two or more windings, (c) three or more windings.**

IMPORTANT DEFINITIONS

AUTOTRANSFORMER — A transformer with a single winding.

COEFFICIENT OF COUPLING (k) — A numerical rating between 0 and 1 that specifies the degree of magnetic coupling between two circuits. Maximum coupling is 1 and no coupling is 0.

COUNTER ELECTROMOTIVE FORCE (CEMF) — The voltage induced in a wire by self-induction which opposes the applied voltage. Also called "back emf."

EDDY CURRENT — Circulating current produced in connecting materials by a varying magnetic field. Eddy currents are undesirable in the core of a transformer.

FLUX LINKAGE — The linking of the magnetic lines of force with the conductors of a coil. The value obtained by multiplying the number of turns in the coil by the number of magnetic lines of force passing through the coil.

HENRY (H) — The basic unit of inductance. One henry is the inductance which induces a cemf of 1 volt when the current is changing at a rate of 1 ampere per second.

HYSTERESIS — The lagging of induced magnetism behind the magnetizing force.

INDUCTANCE — The property of a circuit or coil that causes an electromotive force to be set up due to a change of current in the circuit or coil.

INDUCTIVE COUPLING — The coupling or linkage of two circuits by the changing magnetic lines of force. See also MUTUAL INDUCTION.

INDUCTOR (L) — A coil of wire which has the property of inductance.

LAMINATIONS — Thin layers or sheets. As used here, the term refers to the thin pieces of iron used to build up the core of a transformer.

LEAKAGE INDUCTANCE — A small inductance associated with those flux lines of a transformer winding which are not magnetically coupled to the other windings of the transformer.

MUTUAL INDUCTANCE (M) — The ability of one conductor to induce an emf in a nearby conductor when the current in the first conductor changes.

IMPORTANT DEFINITIONS (Continued)

MUTUAL INDUCTION — The electromagnetic induction produced by one conductor in another nearby conductor, due to the moving flux of the first circuit cutting the conductors of the second circuit.

PRIMARY (P) — That winding of a transformer which is connected to and receives energy from an external source of electrons. Also, frequently referred to as the input winding.

SECONDARY (S) — That winding of a transformer which receives its energy by electromagnetic induction from the primary. Also, frequently referred to as the output winding. A transformer may have one or more secondaries.

SELF-INDUCTION — The process by which a changing current induces a voltage into the conductor or coil carrying the current.

SELF-INDUCTANCE — The ability of a circuit or coil to induce a voltage within itself.

STEP-DOWN — This refers to a transformer that has fewer turns of wire in the secondary than in the primary, which causes a decrease or step-down of the voltage.

STEP-UP — This refers to a transformer that has more turns of wire in the secondary than in the primary, which causes an increase or step-up of the voltage.

TOROID — This refers to a circular, donut-shaped core used in transformers. Toroid cores are generally molded from powdered iron or wound with silicon steel strips.

TRANSFORMER — An electric device, without moving parts, for transferring electric energy from one or more circuits to one or more other circuits by electromagnetic induction.

ESSENTIAL SYMBOLS AND EQUATIONS

E_P	Primary voltage (volts)
E_S	Secondary voltage (volts)
I_P	Primary current (amperes)
I_S	Secondary current (amperes)
k	Coefficient of coupling
L_1, L_2, L_3	Individual inductances (henries)
L_N	The total number of inductors used in a series or parallel arrangement (henries)
L_P	Primary inductance (henries)
L_S	Secondary inductance (henries)
L_T	Total inductance (henries)
M_m	Theoretical maximum mutual inductance (henries)
M	Mutual inductance (henries)
N	Turns ratio
N_P	Turns in primary
N_S	Turns in secondary

$$L_T = L_1 + L_2 + L_3 + \ldots L_N \tag{1}$$

$$L_T = L_1 + L_2 \pm 2M \tag{2}$$

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots \frac{1}{L_N} \tag{3}$$

$$\frac{E_S}{E_P} = \frac{N_S}{N_P} \tag{4}$$

$$N_S = N_P \frac{E_S}{E_P} \tag{4a}$$

$$N_P = N_S \frac{E_P}{E_S} \tag{4b}$$

ESSENTIAL SYMBOLS AND EQUATIONS
(Continued)

$$E_P = E_S \frac{N_P}{N_S} \qquad (4c)$$

$$E_S = E_P \frac{N_S}{N_P} \qquad (4d)$$

$$N = \frac{N_S}{N_P} \text{ or } N = \frac{N_P}{N_S} \qquad (5)$$

$$N = \frac{E_S}{E_P} \text{ or } N = \frac{E_P}{E_S} \qquad (5a)$$

$$E_P I_P = E_S I_S \qquad (6)$$

$$I_S = I_P \frac{E_P}{E_S} \qquad (6a)$$

$$\frac{I_S}{I_P} = \frac{N_P}{N_S} \qquad (7)$$

$$I_S = I_P \frac{N_P}{N_S} \qquad (7a)$$

$$I_P = I_S \frac{N_S}{N_P} \qquad (7b)$$

$$N_P = N_S \frac{I_S}{I_P} \qquad (7c)$$

$$N_S = N_P \frac{I_P}{I_S} \qquad (7d)$$

$$M_m = \sqrt{L_P L_S} \qquad (8)$$

$$k = \frac{M}{\sqrt{L_P L_S}} \qquad (9)$$

PRACTICE EXERCISE SOLUTIONS

1. There are no moving parts in a normal transformer. The coils of a transformer are stationary and the field moves electrically.

2. False — The field starts from within the conductor and expands outward. Although this occurs very rapidly, it does take some time.

3. self-induction

4. (b) counter emf. — It is called counter emf (counter electromotive force) because it opposes the voltage that causes the action.

5. False — Counter emf dies out when the magnetic field stops changing, not when the applied voltage is removed.

6. True — When caused by a collapsing field, the self-induced voltage will attempt to maintain the original current instead of opposing it. This is why arcing often occurs when a switch is opened.

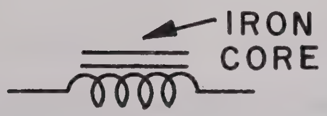
7. False — INDUCTANCE is the property possessed by a circuit. It is present with or without current, just as a resistor has resistance with or without current.

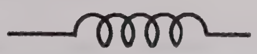
8. Inductance depends on the number of magnetic lines of force that cut the conductor for each ampere change of current. A coil has greater inductance than a straight wire, and a coil with an iron core has greater inductance than one without.

9. henry (H).

10. 7; .35; .0012

11.

(a) 

(b) 

12. False — Energy must be expended to develop a magnetic field initially and to move the magnetic lines of force if a varying field is required.

13. magnetic field

14. (b) mutual induction.

PRACTICE EXERCISE SOLUTIONS (Continued)

15. False — A constant magnetic field, even at maximum, does not permit any induction.

16. Mutual inductance (M).

17. False — MUTUAL INDUCTION is an action which occurs only when there is a current flow. MUTUAL INDUCTANCE is present with or without current, since this is the ability or property of a circuit and not an action.

18. inductive coupling

19. Multiply the number of magnetic lines of force by the number of turns of the coil through which the magnetic lines pass.

20. 10 henries. — With no magnetic coupling the total series inductance is determined by adding the values of the series inductors:
$L_T = L_1 + L_3 + L_3 = 5 \text{ henries} + 4 \text{ henries} + 1 \text{ henry} = 10 \text{ henries}.$

21. 6 henries. — With magnetic coupling and opposing magnetomotive forces, the total series inductance is determined as follows:
$$L_T = L_1 + L_2 - 2M = 3 \text{ henries} + 7 \text{ henries} - 2 \times 2 \text{ henry}$$
$$= 3 \text{ henries} + 7 \text{ henries} - 4 \text{ henries} = 6 \text{ henries}.$$

22. 1 henry. — Parallel inductances are determined using the following expression:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} = \frac{1}{6 \text{ henries}} + \frac{1}{3 \text{ henries}} + \frac{1}{2 \text{ henries}}$$

$$= \frac{1}{6 \text{ henries}} + \frac{2}{6 \text{ henries}} + \frac{3}{6 \text{ henries}} = \frac{6}{6 \text{ henries}}$$

$$\frac{L_T}{1} = L_T = \frac{{}^{1}\cancel{6} \text{ henries}}{{}^{1}\cancel{6}} = 1 \text{ henry.}$$

23. The first or primary action of setting up the magnetic field occurs around the primary coil. The second action, the induction of a voltage, takes place in the secondary.

24. True — A transformer will not operate with a steady current in its primary; however, satisfactory operation can occur if the primary current is interrupted by a switching arrangement, such as an inverter. This system is sometimes used in battery-operated equipment. However, a transformer is normally operated with ac applied to the primary.

PRACTICE EXERCISE SOLUTIONS (Continued)

25. A transformer core provides a magnetic circuit or path for coupling the magnetic flux of the primary to the secondary.

26. The scale on each lamination acts as an insulator and does not allow electric current to pass from one layer of the core to the next. The current in the core which occurs from the transformer action is greatly reduced and this minimizes a loss that would otherwise occur.

27. The toroidal core reduces flux leakage, resulting in a more efficient transformer.

28. True — Electric currents in a transformer core (eddy currents) heat the transformer and waste power. These currents are reduced by using a core made up of insulated, thin sheets of soft iron rather than a solid block of iron. These sheets are called laminations.

29. (a) proper selection of core material. — The core of a transformer acts as a temporary magnet that must reverse its polarity each time the primary current changes direction. Some grades of iron can do this more easily than others and thus produce less loss.

30. 250 turns — $N_S = \frac{N_P E_S}{E_P} = \frac{100 \times 50}{20} = 250.$

31. 22 volts. — In a step-down transformer the output voltage is equal to input voltage times the secondary turns, divided by the primary turns.

    This is Equation 4d: $E_S = E_P \frac{N_S}{N_P} = 110 \times \frac{1}{5} = 22$ volts.

32. 3 to 1 (sometimes written 3:1) step-up — In a transformer, the turns ratio is the same as the voltage ratio. Using Equation 5a:

    $N = \frac{E_S}{E_P} = \frac{330}{110} = 3.$ This is indicated as 3:1.

33. 440 volts. — Using Equation 4d:

$$E_S = E_P \frac{N_S}{N_P} = 110 \frac{1000}{250} = 110 \times 4 = 440 \text{ volts.}$$

34. The primary power. — Some unavoidable losses in the core and windings are not considered here; although transformer design cannot neglect these, they are usually very small and do not affect our lesson requirements.

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1034A
EXAMINATION CHECK SHEET

1034A

1. D - WHEN PLACED WITHIN A COIL, AN IRON CORE -- INCREASES THE INDUCTANCE.
The iron core reduces the reluctance of the magnetic circuit, thereby increasing the inductance.

2. D - SELF INDUCTION IN A STRAIGHT WIRE OCCURS WHEN THE MAGNETIC FIELD -- IS CHANGING.
To develop a voltage, either the conductor or the magnetic field must be moving.

3. A - WHEN THE CURRENT THROUGH AN INDUCTOR STARTS TO CHANGE, THIS CURRENT IS PREVENTED FROM INSTANTLY REACHING ITS FINAL VALUE BY THE -- COUNTER EMF.
The induced counter emf is of such a polarity to oppose the change in current.

4. A - ENERGY IS STORED IN A MAGNETIC FIELD ABOUT AN INDUCTOR DUE TO THE CURRENT THROUGH IT. WHEN THE CURRENT DECREASES, THE COLLAPSING MAGNETIC FIELD -- RETURNS ENERGY TO THE CIRCUIT.
This returned energy is in the form of the counter emf.

5. A - WHENEVER A MAGNETIC FIELD CUTS A CONDUCTOR -- A VOLTAGE IS INDUCED.
A voltage is induced in a conductor whenever there is relative motion between the conductor and the magnetic field.

6. C - THE ACTION OF A MAGNETIC FLUX FROM ONE CIRCUIT CUTTING THE CONDUCTORS OF THE SECOND CIRCUIT IS -- MUTUAL INDUCTION.
The factor mutual inductance is a measure of the mutual induction and takes into account the number of turns on the windings and the degree of coupling.

7. D - TRANSFORMERS WORK BECAUSE -- ELECTROMAGNETIC INDUCTION IS POSSIBLE.
In a transformer, electromagnetic induction is provided by a moving magnetic field.

8. C - IF THE PRIMARY VOLTAGE OF A TRANSFORMER IS 120 VOLTS AND THE SECONDARY VOLTAGE IS 5 VOLTS, WHAT IS THE TURNS RATIO? -- 24:1.
The turns ratio is equal to:

$$N = \frac{E_P}{E_s} = \frac{120 \text{ volts}}{5 \text{ volts}} = 24$$

Expressing the turns ratio with respect to 1 yields 24:1 step-down.

9. A - UNITS OF INDUCTANCE ARE IN -- HENRIES.
The basic unit of inductance is the henry, which would cause a cemf of 1 volt to be developed by a change of current of one ampere per second.

10. B - SUPPOSE THAT THE PRIMARY INDUCTANCE OF A TRANSFORMER IS 250 MILLIHENRIES AND THE SECONDARY INDUCTANCE IS 100 MILLIHENRIES. IF THE COEFFICIENT OF COUPLING IS 0.85, WHAT IS THE MUTUAL INDUCTANCE? -- .134 HENRY.
Mutual inductance is equal to:

$$\begin{aligned} M &= k\sqrt{L_pL_s} \\ &= .85\sqrt{250 \times 10^{-3} \times 100 \times 10^{-3}} = .85\sqrt{2.5 \times 10^{-1} \times 1 \times 10^{-1}} \\ &= .85\sqrt{2.5 \times 10^{-2}} = .85 \times 1.58 \times 10^{-1} \\ &= 1.34 \times 10^{-1} = .134 \text{ henry or } 134 \text{ millihenries} \end{aligned}$$

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1034A

Example: Directions for delivery of a letter or package are called

A ■
B ☐
C ☐
D ☐

A. an address. B. an embrace. C. a receipt. D. an insect.

1. **When placed within a coil, an iron core**
(A) reduces the flux. (B) allows fewer lines to cut the conductor. (C) decreases the inductance. (D) increases the inductance.
A ☐ B ☐ C ☐ D ☒

2. **Self-induction in a straight wire occurs when the magnetic field**
(A) is minimum. (B) is at rest. (C) is maximum. (D) is changing.
A ☐ B ☐ C ☐ D ☒

3. **When the current through an inductor starts to change, this current is prevented from instantly reaching its final value by the**
(A) counter emf. (B) resistance of the coil. (C) eddy currents. (D) applied emf of the circuit.
A ☒ B ☐ C ☐ D ☐

4. **Energy is stored in a magnetic field around an inductor due to the current through it. When the current decreases, the collapsing magnetic field**
(A) returns energy to the circuit. (B) takes energy from the circuit. (C) increases the flux. (D) does not induce a voltage.
A ☒ B ☐ C ☐ D ☐

5. **Whenever a magnetic field cuts a conductor,**
(A) a voltage is induced. (B) electrons flow even though the circuit is incomplete. (C) a voltage is not induced. (D) the voltage induced in the conductor completely cancels the magnetic field.
A ☒ B ☐ C ☐ D ☐

6. **The action of a magnetic flux from one circuit cutting the conductors of the second circuit is**
(A) stepping-up. (B) rectifying. (C) mutual induction. (D) resistance.
A ☐ B ☐ C ☒ D ☐

7. **Transformers work because**
(A) magnetic fields oppose flux linkage. (B) magnetic fields are always stationary. (C) there is no flux linkage. (D) electromagnetic induction is possible.
A ☐ B ☐ C ☐ D ☒

8. **If the primary voltage of a transformer is 120 volts and the secondary voltage is 5 volts, what is the turns ratio?**
(A) 5:1. (B) 1:12. (C) 24:1. (D) 8:1.
A ☐ B ☐ C ☒ D ☐

9. **Units of inductance are in**
(A) henries. (B) electrons. (C) volts. (D) induction.
A ☒ B ☐ C ☐ D ☐

10. **Suppose that the primary inductance of a transformer is 250 millihenries and the secondary inductance is 100 millihenries. If the coefficient of coupling is 0.85, what is the mutual inductance?**
(A) 100 millihenries. (B) .134 henries. (C) 134 henries. (D) 250 millihenries.
A ☐ B ☒ C ☐ D ☐

EXPERIMENT 4

TRANSFORMERS

PARTS NEEDED

1 - Design Console

1 - Multimeter and Test Leads

OBJECTIVE

The purpose of this experiment is to investigate the action of a transformer and determine the turns ratio.

PROCEDURE

1. Refer to Figure 4-1. This figure shows the schematic diagram of the transformer used in the design console. The voltages shown are the rated voltages. The rated voltages are determined with a load connected to the transformer. This experiment will be done with no load, so your voltages will be somewhat higher.

2. Turn the design console on/off switch to the on position and measure the voltage between all of the points shown on the schematic. Record your measurements below.

E1-8____________________Vac

E2-5____________________Vac

E10-5____________________Vac

E6-7____________________Vac

E2-10____________________Vac

E4-9____________________Vac

E4-3____________________Vac

E3-9____________________Vac

Turn the design console on/off switch to the off position.

3. Using the measured primary voltage and the measured voltage between terminals 1 and 8, 2 and 5, and 9 and 4, calculate the turns ratio of each secondary. Your calculations should look similar to those below where the rated values are used:

$$\frac{N_s}{N_p} = \frac{E_s}{E_p} = \frac{120}{120} = 1.00$$

Turns ratio 1 to 1 (used for isolation)

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{120}{12.6} = 9.5$$

Turns ratio 9.5 to 1 step-down

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{120\text{V}}{30} = 4$$

Turns ratio 4 to 1 step-down

CONCLUSION

In this experiment we see that a number of different voltages can be obtained from one transformer. The different voltages are obtained by changing the turns ratio between the secondary and the primary.

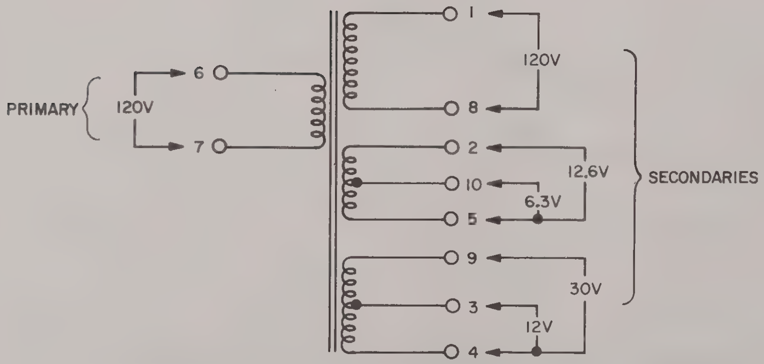

FIGURE 4-1

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9502-4A
EXAMINATION CHECK SHEET

1. A - IF THE SECONDARY VOLTAGE OF A TRANSFORMER IS HIGHER THAN THE PRIMARY VOLTAGE, THE TRANSFORMER IS -- STEP-UP.
The term step refers to the voltage across the secondary with respect to the voltage across the primary. If the secondary voltage is higher than the primary voltage the transformer is a step-up transformer.

2. B - IF THE PRIMARY VOLTAGE IS HIGHER THAN THE SECONDARY VOLTAGE, THE TRANSFORMER IS -- STEP-DOWN.
If the secondary voltage is lower than the primary voltage the transformer is step-down.

3. B - THE WINDING BETWEEN TERMINALS 9 AND 4 IN FIGURE 4-1 IS, WITH RESPECT TO THE PRIMARY, -- STEP-DOWN.
The voltage between terminals 9 and 4 is lower then the primary, hence the winding is step-down.

4. B - IF THE NUMBER OF TURNS IN THE PRIMARY IS 100 AND THE NUMBER OF TURNS IN THE SECONDARY IS 10, THE TRANSFORMER IS -- STEP-DOWN.
If the number of turns in the secondary is lower then the number of turns in the primary the transformer is step-down.

5. A - IF THE SECONDARY VOLTAGE IS 90 VOLTS AND THE PRIMARY VOLTAGE IS 360 VOLTS, WHAT IS THE TURNS RATIO? -- 4 TO 1 STEP-DOWN.

$$N = \frac{360}{90} = 4 = 4:1 \text{ step-down}$$

CAPACITORS

1037

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A variable capacitor is used as the tuning control in this stereo FM receiver to select the desired station.

Courtesy Sherwood Electronic Laboratories, Inc.

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> *Happiness and usefulness — not wealth — are the true measure of success, and they are within the reach of every man.*
>
> *—J. Ogden Armour*

CAPACITORS

Practically every electronic device, no matter how small or simple it may be, has at least one of each of the following components: inductors, resistors and capacitors. Inductors and resistors have already been described, and next we will study the properties and actions of capacitors. The early experimenters called these units condensers, a term which is still sometimes used. However, the name *capacitor* more accurately describes the electric action, and it is now the more commonly used name of the two.

One definition of capacitance is that it is the ability of a circuit (or a circuit device) to oppose any change in circuit voltage. (This definition is somewhat similar to the property of inductance, which opposes any change in circuit current.) Another definition for capacitance is that it is the ability of a circuit (or device) to store electric energy in an electric field. Both definitions are correct; they merely describe the action of a capacitor in different ways.

Just as the inductor exhibits the property of inductance and the resistor has resistance, the **CAPACITOR** is the electronic device that has the property of **CAPACITANCE.**

In general, a capacitor consists of two conducting surfaces separated by an insulating material. The conducting surfaces are called the **PLATES** of the capacitor, and the insulating material is called the **DIELECTRIC**. This dielectric material can be any good insulator, including air. The structure and composition may vary quite a bit from one type of capacitor to the next, but it is the purpose of all capacitors to store electric energy supplied by some external source.

CHARGING OR STORING ACTION

In the circuit of Figure 1, the shaded rectangles represent a cross-sectional view of the capacitor plates, which are separated by an air dielectric. The battery supplies electric pressure, and the switch provides a control action by connecting or disconnecting the battery from the circuit. A resistor is connected in series with the capacitor, and the voltmeters connected across the resistor and capacitor indicate the voltages across both of these components.

As long as the switch is open, there is no electron flow, and both meters indicate zero. Before the switch is closed, the capacitor plates are electrically neutral; that is, the plates are at zero potential.

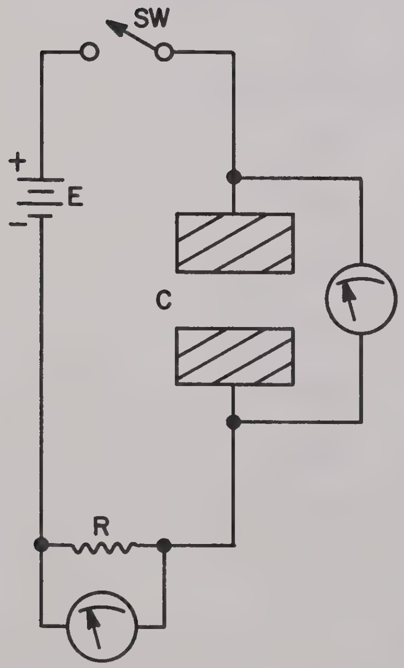

Figure 1

When the switch is closed, conditions in the circuit change. The upper plate of the capacitor connects through the switch to the positive terminal of the battery and the lower plate connects through resistor R to the negative terminal of the battery. The positive terminal of the battery, therefore, is positive with respect to the zero potential on the upper plate of the capacitor, and the negative terminal of the battery is negative with respect to the zero potential on the lower plate of the capacitor. Whenever a difference of potential exists between two charged bodies and a suitable path is provided from one to the other, electrons move from the more negative to the more positive of the two bodies. Moving through the connecting wires between the battery terminals and the capacitor plates, electrons flow from the negative battery terminal, through resistor R, to the lower plate of the capacitor. Electrons also move from the upper plate through the closed switch to the positive terminal of the battery. This movement of electrons continues until the capacitor plates are at the same potentials as the battery terminals to which they are connected.

The electrons do not pass through the dielectric in the capacitor. However, electrons move between the battery terminals and capacitor plates as the capacitor charges. Thus, current exists in a circuit containing a capacitor during the brief interval in which the charging takes place, and the current stops as soon as the capacitor reaches its full charge.

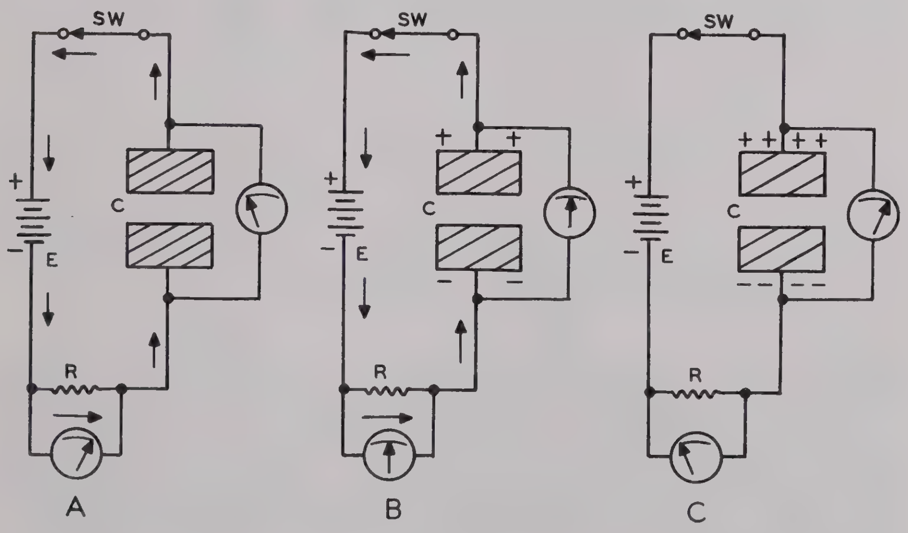

Figure 2

To follow the action in detail, assume that switch SW has just been closed. The capacitor plates are at zero potential at this instant, and electrons move from the negative terminal of the battery to the lower plate of the capacitor. At the same time, electrons pass from the upper plate of the capacitor to the positive terminal of the battery. The movement of electrons represents a **DISPLACEMENT CURRENT**, and the arrows in Figure 2A trace the path of the electrons.

In series with capacitor C, resistor R must carry the charging current. Whenever electrons flow through a resistor, a voltage is developed across the resistor. The magnitude of this voltage depends upon the magnitude of current. Since the charging current is large at the instant the charge begins, the voltage across resistor R also is large. The meter connected across resistor R shows a large deflection at the beginning of the charge action in Figure 2A. At this time, the capacitor has not taken on enough charge to provide a noticeable deflection on its meter.

As the action continues, electrons moving from the negative terminal of the battery to the lower plate of the capacitor spread uniformly over the capacitor plate. These electrons, each carrying its own negative charge, tend to repel other electrons which attempt to leave the battery terminal and move to the capacitor plate. Therefore, an opposition is set up to the electron movement, and the charging current decreases. Since the voltage across resistor R is determined by the current passing through this resistor, the meter shows a decrease of resistor voltage in Figure 2B. The rising charges on the capacitor plates are shown by the + and — symbols, and the resulting voltage causes a deflection of the meter pointer.

Ordinarily, the number of electrons that can be accumulated on the negative plate of a capacitor before the charging period ends is limited by the repelling effect of the electrons themselves. Each electron carries a negative charge and repels other electrons by virtue of this charge. As the electrons accumulate on the negative plate of a capacitor, they oppose the flow of other electrons from the battery to the capacitor plate.

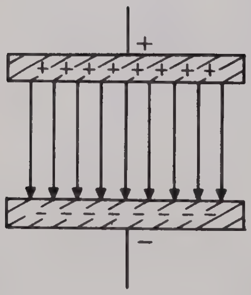

Figure 3

When two bodies of unlike charges are placed close to each other, an electric field is set up between them. Such a field exists between the closely spaced plates of a capacitor when the charges form on the plate. As illustrated in Figure 3, this field is assumed to consist of lines of force extending through the dielectric from positive to negative. (An electric field can exist in an insulator, even though the electrons themselves cannot pass through the dielectric material.)

The influence of the positive plate, extending through the dielectric by means of the electric field, serves to attract electrons; it effectively cancels a part of the repelling effect of the electron charges. Since the repelling effect of the electrons is a limiting factor in the storing of electrons on the plate, the partial cancellation of this effect makes it possible for a greater number of electrons to be transferred to the capacitor during the charge interval. For a given amount of applied voltage, the electric field between the plates makes it possible for a larger charge to be developed in the capacitor.

While the switch is closed, the capacitor continues to charge, until the voltage across the capacitor is equal to the full applied voltage. At that time, the capacitor is said to be completely **CHARGED** to the battery voltage. As illustrated in Figure 2C, there is no further electron movement, or charge current, and the voltage across resistor R drops to zero. The meter across the capacitor shows a large deflection, and more + and — symbols have been added to the capacitor plates to represent the full charge.

If the switch is opened or the connecting wires are removed from the battery terminals after the capacitor is charged, the capacitor plates remain at the potential difference developed by the battery. Assuming that there is no leakage current, the excess electrons on one plate are unable to reach the other electron deficient plate, and the capacitor holds its charge.

DISCHARGE ACTION

The capacitor will hold its charge until a suitable discharge path is provided. In order for discharge to take place, there must be a complete circuit between the capacitor plates, such as that illustrated in Figure 4. When

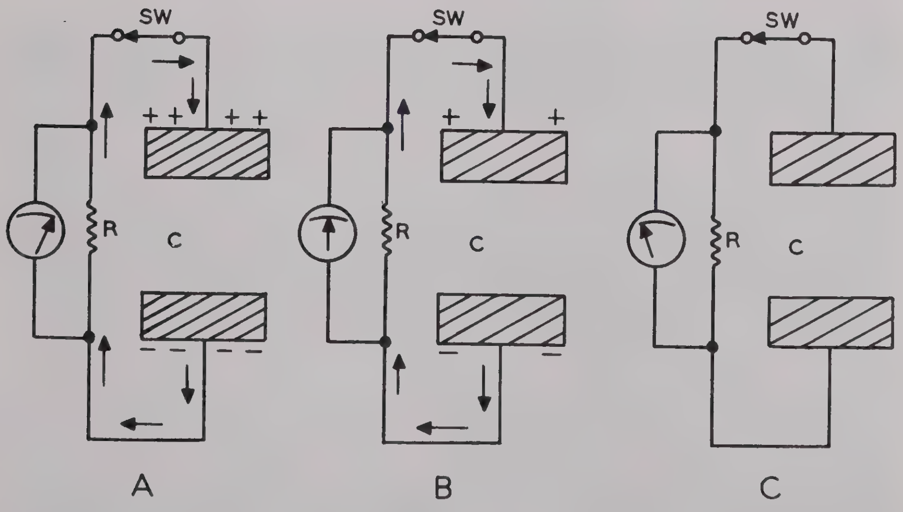

Figure 4

the path is provided, electrons move from the negative plate of the capacitor around through the circuit to the positive plate.

Figure 4A shows the conditions in the circuit at the instant the switch is closed. Resistor R is connected across the capacitor plates to provide the discharge path, and electrons move in the direction of the arrows. If we assume that the capacitor is fully charged at the instant the switch is closed, the discharge current is relatively large at this instant. Again, the current is carried by the series resistor and a large voltage is shown on the meter. The discharge action continues in Figure 4B, where the charge has been reduced by the movement of electrons from the negative plate around to the positive plate. The difference of potential between the capacitor plates, which serves as the voltage source for the discharge current, has decreased, and there is a corresponding decrease in voltage across resistor R.

Finally, as illustrated in Figure 4C, the capacitor is completely **DISCHARGED**. There is no difference of potential between the plates, and current flow stops. With no current passing through resistor R, there is no voltage indicated on the meter.

BLOCKING DC AND PASSING AC

Based on the previous explanation, it can be said that a capacitor "blocks" the direct current of a battery, once the capacitor has charged to the applied voltage. That is, current exists only for those brief intervals during which the capacitor charges or discharges.

Suppose that it were possible to reverse the polarity of the applied voltage in the capacitor circuit. An arrangement of this type is illustrated in Figure 5A, where a two-position switch connects either battery E_1 or E_2 to the capacitor circuit. (The capacitor, C, shown in Figure 5A, is the normal schematic symbol that will appear in future figures.) With the switch in position 1, battery E_1 serves as the voltage source, and electrons flow in the direction of the solid arrows. This electron flow charges capacitor C so that its upper plate is positive with respect to its lower plate. When the capacitor is charged to the battery voltage, the current ceases.

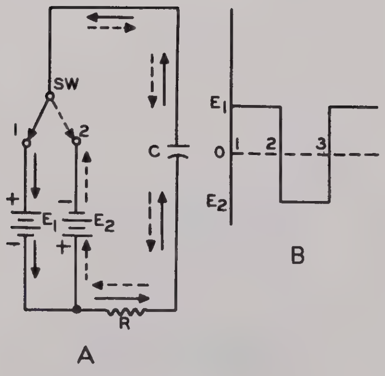

Figure 5

If the switch is now moved to position 2, the polarity of the applied voltage reverses. If capacitor C has charged to the voltage of E_1 during the first "alternation," it must discharge to zero, and then charge in the opposite direction, when the polarity of the applied voltage reverses. As explained previously, the discharge consists of a movement of electrons from the negative plate around through the circuit to the positive plate. This path is traced by the dashed arrows, from the lower plate through resistor R and battery E_2 to the upper plate of the capacitor. When the capacitor is charged to the voltage of E_2, the current ceases.

Switching back to position 1 causes the polarity of the source to reverse once again. Then, capacitor C must discharge through E_1 and R, then charge to the voltage of E_1. The path is traced by the solid arrows, and the current ceases when the capacitor voltage equals that of E_1.

The effect of switching is illustrated graphically in Figure 5B. If we assume that the switch is in position 1 at interval 1 of the curve, we see that voltage E_1 is applied to the circuit. This voltage serves as the source for the capacitor until interval 2, when the switch is moved to position 2. The applied voltage drops to zero and then reverses in polarity so that it now equals E_2. The switch is moved back to position 1 at interval 3, and the applied voltage once again decreases to zero, then increases to the value of E_1.

The resistor carries the charge and discharge currents for both polarities. Therefore, a voltage appears across resistor R at intervals 1, 2 and 3, where the changes in applied voltage take place. When the current passes through the resistor in the direction of the solid arrows, a voltage of one polarity appears, and when the direction of current reverses (as shown by the dashed arrows), the voltage across resistor R is of opposite polarity.

If the switch is moved at a slow rate, the current pulses exist for relatively brief intervals, dropping to zero each time the capacitor reaches its full charge or discharge. However, if the switching speed is increased to a very fast rate, the capacitor never gets a chance to completely charge or discharge; it is constantly in a state of charge or discharge. Then, current is present at all times in the circuit, and an alternating voltage corresponding to the source voltage appears across resistor R. This effect would be similar to replacing the capacitor with a piece of wire.

The battery arrangement of Figure 5A is replaced by an ac generator in Figure 6A. The reversals of polarity of the generator keep the capacitor charging and discharging, and the situation is similar to that of Figure 5A. With displacement current moving back and forth continually between the generator terminals and the capacitor plates, a corresponding voltage appears across the resistor. This is shown in Figure 6B. If the generator varies at a fast enough rate, the changing current passes through the circuit as if no capacitor were present.

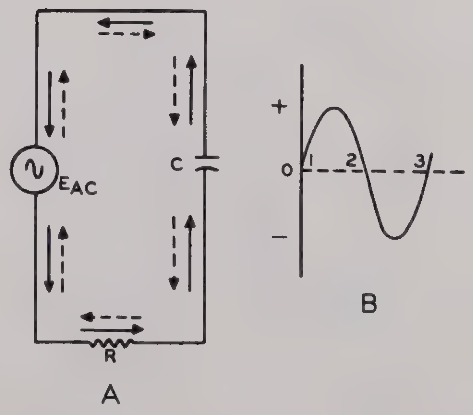

Figure 6

If a capacitor blocks direct current and passes alternating current, what will happen if alternating and direct current sources are combined in a

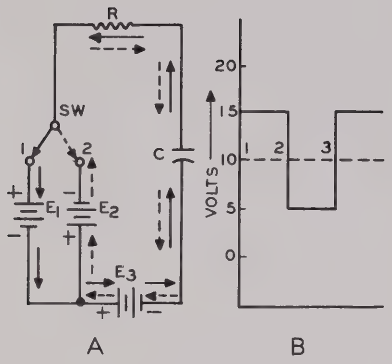

Figure 7

capacitor circuit? To illustrate the action, another battery has been added to the circuit of Figure 5, as shown in Figure 7. Through the switching arrangement, battery voltage E_1 or E_2 may be combined with battery voltage E_3, and the resultant voltage is applied to the series circuit of capacitor C and resistor R. When the switch is in position 1, voltages E_1 and E_3 are in series, and the total voltage is equal to the sum of the two. If voltages E_1 and E_2 are each 5 volts and E_3 is 10 volts, the total voltage applied to the capacitor circuit is $10 + 5$, or 15 volts. When the switch is in position 2, the polarity of E_2 opposes that of E_3, and the total voltage equals the difference between the two, or $10 - 5 = 5$ volts.

This method of combining voltages is illustrated in Figure 7B. The dashed line represents the 10 volts of E_3, which serves as the average voltage in the circuit. If switch SW is moved to position 1 at interval 1, the applied voltage increases from 10 volts to 15 volts, as illustrated by the solid line waveform. Then, when the switch is moved to position 2 at interval 2, the applied voltage decreases from 15 volts to 5 volts. When the switch is moved back to position 1 at interval 3, the total voltage increases to 15 volts.

Notice the similarity between the solid waveform in Figure 7B and that of Figure 5B. The only difference lies in the reference axis. In Figure 5B, the waveform varies above and below zero, while the waveform of Figure 7B varies above and below an axis of 10 volts.

In this circuit, where a constant and varying voltage are combined, it is convenient to think of the resultant voltage as *pulsating dc*, and to consider this pulsating value as consisting of two "components." The average level (the 10-volt level in Figure 7B) is referred to as the "dc component." The increases and decreases around this average level (the variations between + 15 and + 5 in Figure 7B) are known as the "ac component."

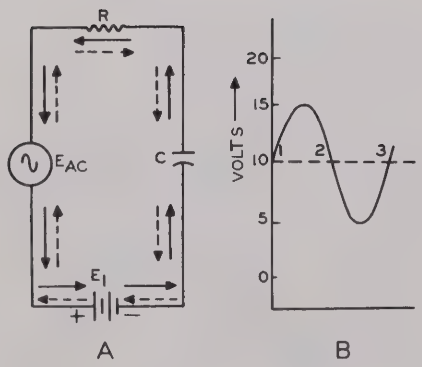

Figure 8

The same reasoning can be applied in Figure 8A, where the E_1-E_2 arrangement of Figure 7A is replaced by an ac generator having a peak amplitude of 5 volts. Once again, the battery provides a steady dc which serves as the reference (dc component) for the graph of Figure 8B. During one alternation of generator voltage, its polarity aids that of battery voltage E_1, and the total voltage rises above the +10-volt level, as shown between intervals 1 and 2 of Figure 8B. Capacitor C charges in the direction of the solid arrows.

Then, the generator voltage decreases and reverses polarity, so that its polarity opposes that of battery voltage E_1. The solid waveform of Figure 8B drops below the +10-volt average level and reaches a low of +5 volts. In line with this decrease in total applied voltage, capacitor C discharges in the direction of the dashed arrows. Whenever the applied voltage increases, the capacitor charges to a higher value. When the applied voltage decreases, as it does when it goes from +15 volts to +5 volts, the capacitor discharges.

To summarize the actions in Figures 7 and 8, the capacitor charges and discharges to follow the variations of the "ac component." In Figure 7, the charge and discharge actions occur only by switching from one position to the other to change the amount of total voltage. Similarly, in Figure 8, the charge and discharge actions occur only when the generator voltage varies to increase and decrease the total voltage. This, in effect, shows that the capacitor "passes" the current changes produced by the variable (or ac) source, while it is unaffected by the steady current from the dc source after developing the initial charge from that source.

These current changes again appear across resistor R. If the switch of Figure 7A or the generator of Figure 8A is changing rapidly enough to keep the capacitor continuously charging and discharging, the voltage across resistor R approximates the solid waveform or ac component of Figure 7B or Figure 8B.

CAPACITANCE

The cycles of storing and discharging the displacement current electrons are the practical demonstration of the capacitor's ABILITY to oppose any change in circuit voltage. This ability we defined earlier as CAPACITANCE.

As with resistance and inductance, capacitance also has a unit of measure. For capacitance the unit of measure is the **FARAD,** abbreviated **F** or fd. Named after Michael Faraday,

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THE FARAD REPRESENTS THE CAPACITANCE OF A CAPACITOR WHICH ACCEPTS A CHARGE OF ONE COULOMB WHEN A VOLTAGE OF ONE VOLT IS APPLIED.

The common unit of electric current, the ampere, is equal to one coulomb per second. Since a coulomb represents about six times 10^{18}, or 6,000,000,000,000,000,000 electrons, a farad is far too large for most practical purposes. For most ordinary needs, it is more convenient in expressing

Charles Augustin Coulomb (1736-1806), a French military engineer, invented the torsion balance to measure the forces of attraction and repulsion of electrically charged bodies. Today, the unit of electrical charge bears his name.

Courtesy Ohmite Manufacturing Co.

capacitance values to use a smaller unit, the microfarad (μF or mfd), which is equal to one-millionth of a farad.

Many capacitors used in electronic circuits have capacitances much less than even a microfarad. To avoid fractions or decimals, a smaller unit, the micromicrofarad ($\mu\mu$F or mmfd), also called the picofarad (pF), is commonly used in expressing these small capacitance values. Currently, the picofarad employs more usage than the micromicrofarad and will be used in this lesson. One picofarad is equal to one-millionth of a microfarad, or one-millionth of a millionth of a farad.

To change farads to microfarads or to change microfarads to picofarads, the decimal point is moved six places to the right. For example, to change the

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CHARGING OR STORING ACTION

DISCHARGE ACTION

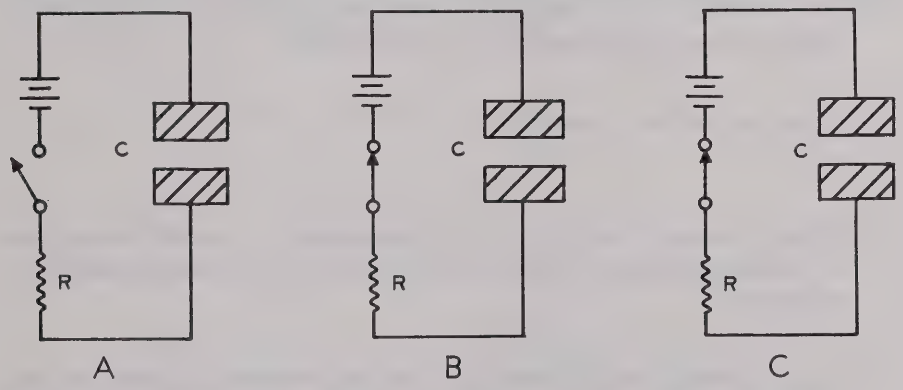
BLOCKING DC AND PASSING AC

1. In a capacitor, the conducting surfaces are called ____________ and the insulating material is called the ____________________.

2. The basic purpose of all capacitors is ______________________________ ______________________.

3. Air is sometimes used as the dielectric in capacitors. True or False?

Shown below are diagrams to illustrate three conditions of charge of a capacitor. Assume that there is no initial charge on the capacitor. Diagram A represents the condition before the switch is closed. Diagram B represents the condition when the capacitor is half charged. Diagram C represents a fully charged condition.



4. In the above diagrams, draw arrows to show the path of electrons. Using + and — signs, show the polarity and relative amount of charge on each capacitor plate in each diagram.

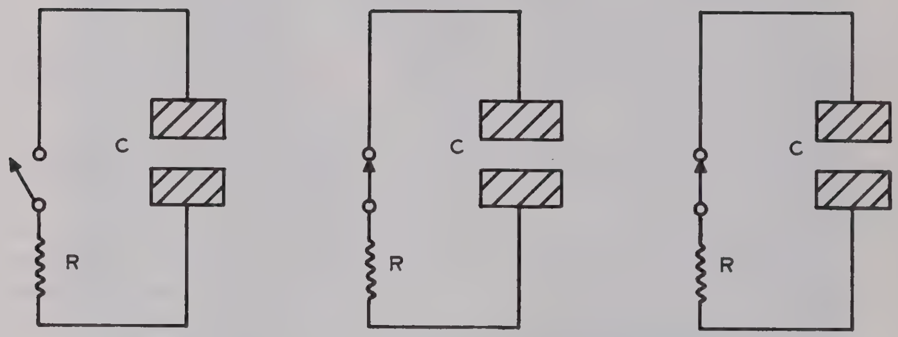
5. What would be the effect of increasing the battery voltage in the previous question?

6. Electrons do not pass through the dielectric of a capacitor. True or False?

7. An electric field can exist in an insulator. True or False?

8. Since electrons cannot pass through the dielectric of a capacitor, it is impossible to have a flow of electrons in a circuit containing a capacitor. True or False?

Shown below are diagrams to illustrate three conditions of discharge of a capacitor. Assume that the capacitor is fully charged with the upper plate positive before the switch is closed. Diagram A represents the condition before the switch is closed. Diagram B represents the condition in which the capacitor is half discharged. Diagram C represents a completely discharged condition.



9. In the above diagram, draw arrows to show the path of electrons. By the use of + and — signs, show the polarity and relative amount of charge on each capacitor plate in each diagram.

10. It can be said that a capacitor ______________ ac but ______________ dc.

11. When a voltage is made up of two components, a constant voltage and a varying voltage, it is often called (a) ac-dc, (b) average voltage, (c) pulsating dc.

12. When pulsating dc is applied to a circuit containing a capacitor, the capacitor charges until it reaches the value of the dc component and all further action is blocked. True or False?

capacitances of .005 F, .00014 μF and .00035 μF to the corresponding μF and pF values, proceed as follows:

$$.005 \text{ F} = 5{,}000 \ \mu\text{F}$$

$$= 5{,}000{,}000{,}000 \text{ pF.}$$

$$.000140 \ \mu\text{F} = 140 \text{ pF.}$$

$$.000350 \ \mu\text{F} = 350 \text{ pF.}$$

To change picofarads to microfarads, or microfarads to farads, move the decimal point six places to the left. For example:

$$275 \text{ pF} = .000275 \ \mu\text{F.}$$

$$300 \ \mu\text{F} = .000300 \text{ F, or } .0003 \text{ F.}$$

Scientific notation provides a convenient means of expressing values of capacitance in the μF and pF range. Since one μF is equal to .000001 farad, one μF equals 10^{-6} farads. In a similar manner, one pF equals 10^{-12} farads. Several examples are shown below:

$$100 \text{ pF} = 100 \times 10^{-12}\text{F or } 1 \times 10^{-10}\text{F.}$$

$$.1 \ \mu\text{F} = .1 \times 10^{-6}\text{F or } 1 \times 10^{-7}\text{F.}$$

$$50 \text{ pF} = 50 \times 10^{-12}\text{F or } 5 \times 10^{-11}\text{F or } 5 \times 10^{-5} \ \mu\text{F.}$$

$$.47 \ \mu\text{F} = .47 \times 10^{-6}\text{F or } 4.7 \times 10^{-7}\text{F or } 4.7 \times 10^{5} \text{ pF.}$$

ENERGY STORED IN A CAPACITOR

When a capacitor is connected across a battery or other source of voltage, work is done in charging the capacitor; this work is stored as electric energy. When it discharges, the capacitor returns this stored energy to the circuit.

The **CHARGE** of the capacitor is a measure of the energy it can store, which corresponds to the quantity of electrons transferred when a given amount of voltage is applied. Since a capacitance of one farad represents one coulomb per volt, the expression may be written in abbreviated form as an equation:

$$C = \frac{Q}{E} \tag{1}$$

where: C is the capacitance in farads,

Q is the charge in coulombs, and

E is the applied voltage in volts.

A capacitor that accepts a charge of 10 coulombs when 5 volts are applied has a capacitance of:

$$C = Q/E = 10/5 = 2 \text{ farads.}$$

Like Ohm's Law, the capacitor charge expression contains three quantities, and it may be used to determine the unknown quantity when the other two are known. When the charge and capacitance are known, the voltage may be determined by means of:

$$E = \frac{Q}{C} \tag{1a}$$

If the charge in a capacitor is 5 coulombs and the capacitance is .5 farad, the voltage is:

$$E = \frac{Q}{C} = \frac{5}{.5} = 10 \text{ volts.}$$

To determine the charge when the capacitance and voltage are known, the expression is:

$$Q = CE. \tag{1b}$$

For example, what is the charge when the capacitance is 2 farads and the voltage between the plates is 100 volts?

$$Q = CE = 2 \times 100 = 200 \text{ coulombs.}$$

$I = \frac{C.E}{2}$ $\frac{Q}{2}$

The expression $Q = CE$ indicates the quantity of electrons stored in a capacitor. The energy required to drive the electrons onto one plate and move them off the other can be found from a simple expression. This value of energy is the actual amount of energy stored in the capacitor. The capacitor energy, measured in joules (or watt-seconds), is:

$$E_n = \frac{CE^2}{2} \tag{2}$$

where: E_n is the energy in joules or watt-seconds,

E is the charging voltage in volts, and

C is the capacitance in farads.

As an example, let's determine the energy stored in a 40 μF capacitor charged to 300 volts. Substituting these values into Equation 2:

$$E_n = \frac{CE^2}{2} = \frac{40 \times 10^{-6} (3 \times 10^2)^2}{2}$$

$$= \frac{4 \times 10^{-5} \times 9 \times 10^4}{2}$$

$$= \frac{36 \times 10^{-1}}{2} = 1.8 \text{ joules (watt-seconds).}$$

FACTORS INFLUENCING CAPACITANCE

Plate Area

To illustrate the effect of plate area on capacitance, assume that the plates of the capacitor shown in Figure 9A have an area of one square foot, and that the capacitance is one farad. Because of the applied voltage, electrons are drawn from the upper plate, which becomes positive, and are transferred through the battery to the lower plate, which becomes negative. These electrons spread out uniformly on the negative plate.

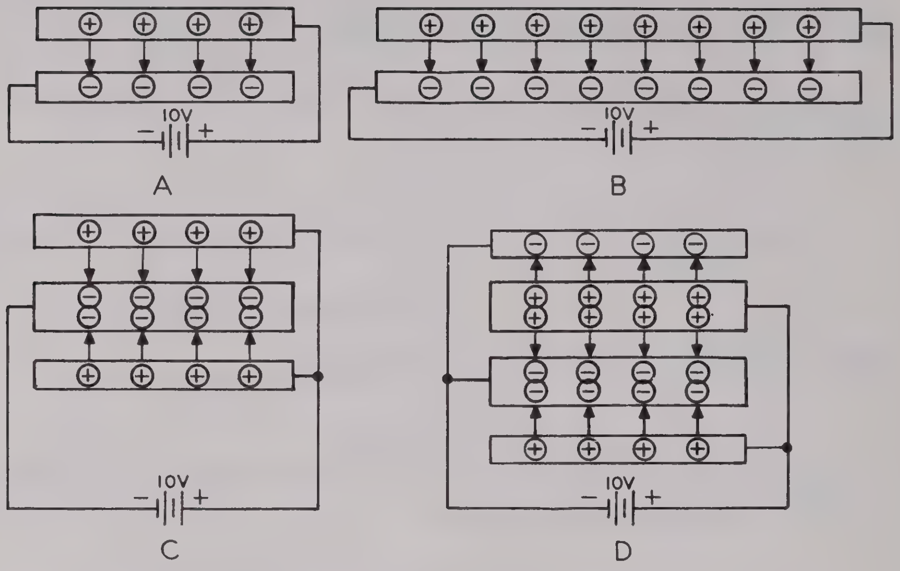


Figure 9

Now, suppose that the plate area is doubled, as shown in Figure 9B. Since the transferred electrons can spread over a surface twice as large, twice as many electrons can be removed from the upper plate, and twice as many can be accumulated on the lower plate, before these electrons repel with enough force to completely stop the electron flow. Although the applied voltage remains the same, the capacitor now contains twice the charge it held when the plates were one foot square. Doubling the plate area doubles the charge stored for a given voltage and, as a result, doubles the capacitance.

Instead of having just two very large plates to obtain the required capacitance, many commercial capacitors are constructed with alternate layers of plates. To illustrate the increase of capacitance by this method of construction, in Figure 9C, a third plate with the same area has been added to the capacitor of Figure 9A. It is placed below the negative plate and, like the upper plate, is connected to the battery's positive terminal.

In this case, the action between the upper side of the bottom plate and the underside of the middle plate is exactly the same as the action between the lower side of the upper plate and the upper side of the middle plate. Since this arrangement provides twice the active plate area, twice the electric energy can be stored for a given voltage. Therefore, the capacitor of Figure 9C has twice the capacitance of the one in Figure 9A.

Adding a fourth plate, either above or below those of Figure 9C, and connecting it to the battery negative terminal, provides another square foot of active area. With four plates, the capacitor of Figure 9D has three times the capacitance of the two-plate unit of Figure 9A.

Plate Spacing

A second factor that determines the capacitance is the spacing between the plates. The smaller the distance between the plates of a capacitor, the thinner the dielectric, and the larger the capacitance. A larger distance between the plates produces a thicker dielectric, which results in less capacitance.

Remember that the electric field between the plates has a very important effect on the amount of charge that can be stored at a particular value of applied voltage. The attracting or repelling properties of electric charges vary inversely as the square of the distance between them; if the capacitor plates are relatively far apart, the effects of the field are not as great as when the plates are closer to each other.

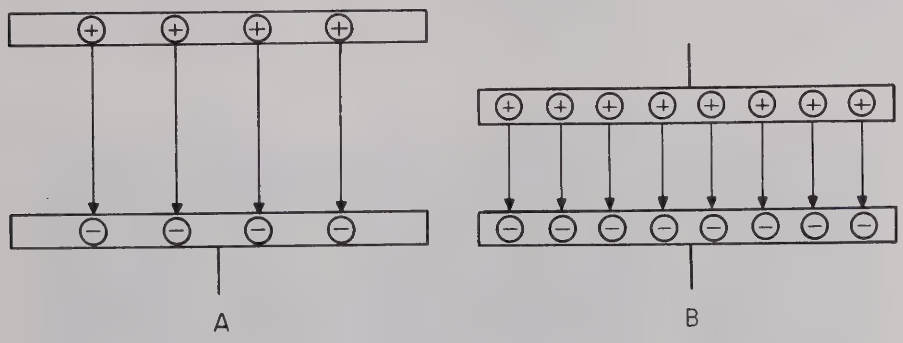


Figure 10

In Figure 10B, the plates of the capacitor are closer together than are those in Figure 10A. Although the dimensions of the plates are the same, the field is strengthened by reducing the plate spacing in Figure 10B. As indicated by the increased number of + and — symbols on the plates, a greater number of electrons can be transferred or a larger charge can be developed, if the plates are moved closer together. All other factors remaining the same, the capacitance varies inversely with the distance between the plates.

Dielectric Material

A third method of changing the capacitance is to use a different dielectric material for the insulation between the plates of the capacitor. To illustrate the action, a dielectric material has been placed between the plates of the capacitor in Figure 11. A few of the dielectric molecules are shown and, for simplicity, their charges are represented by a single positive and negative sign. With no charge on the capacitor, the molecular charges have a random distribution throughout the dielectric, as shown in Figure 11A.

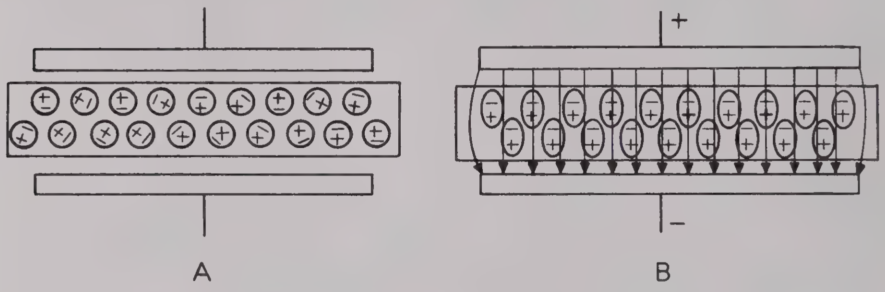
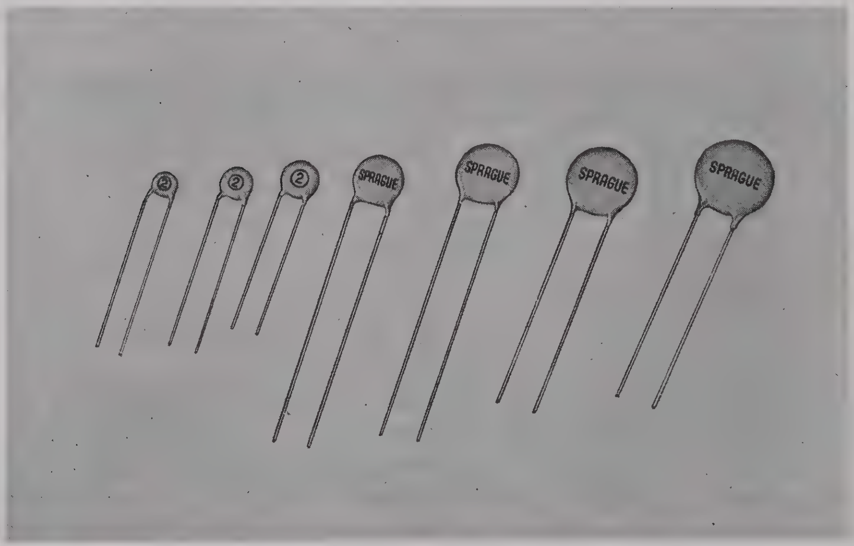


Figure 11

When the capacitor becomes charged as in Figure 11B, the charges in the molecules attempt to line up in the direction of the electric field, with the



The above photo shows several sizes of ceramic dielectric capacitors.
Courtesy Sprague Products Co.

negative charges toward the positive plate and the positive charges toward the negative plate. Due to the force of the **ELECTRIC FIELD**, the paths of the electrons are no longer circular, but become oval, as illustrated.

All of the molecules in the dielectric do not align themselves with the electric field. The number that do align with the field depends upon the voltage and the material used. With a given voltage, the degree to which the molecules of a material align themselves with the electric field is called the **DIELECTRIC CONSTANT (k)** of the material. The larger the number of molecules aligning themselves with the electric field, the larger the dielectric constant.

As a standard for comparison, the dielectric constant of a vacuum is considered as 1. However, there is only a slight difference between the dielectric constant of a vacuum and that of air (1.0006) and air is generally assumed to be the standard of comparison and it too is given a dielectric constant of 1. Other common materials have the approximate dielectric constants shown in Table 1. (The variations between the low and high limits are due to differences between the grades and qualities of the materials.)

TABLE 1

Bakelite	4 to 8
Castor Oil	4 to 5
Ceramic	6 to over 1,000
Kerosene	2 to 3.5
Mica	4 to 7.5
Paper	2 to 4
Paraffin Wax	2 to 2.5
Distilled Water	78 to 81

The larger the dielectric constant of the dielectric material, the larger the capacitance of the capacitor, if all other factors remain the same. For example, suppose that two plates are spaced a fixed distance apart in air, and the resulting capacitor has a capacitance of 1 μF. Without moving the plates, the capacitance would be increased to 6 μF if the air between the plates were replaced by bakelite with a dielectric constant of 6.

To summarize the factors which affect the capacitance of a capacitor, the capacitance is: (1) directly proportional to the area of the plates, (2) inversely proportional to the distance between the plates, and (3) directly proportional to the dielectric constant. By proper consideration of these factors, capacitors can be made in numerous sizes and capacitances.

The factors which determine the value of a capacitor (plate area, spacing and dielectric constant) can be put together in an expression to determine the actual value of capacitance. The capacitance of a simple two-plate capacitor is equal to:

$$C = \frac{0.225\ kA}{d} \tag{3}$$

where: C is the capacitance in pF,

k is the dielectric constant,

d is the spacing between the plates in inches, and

A is the plate area in square inches.

As an example, suppose that we have an air dielectric capacitor with plates 3 inches on a side (9 square inches) and a plate spacing of .1 inch. The value of capacitance is therefore:

$$C = \frac{0.225\ kA}{d} = \frac{0.225 \times 1 \times 9}{.1}$$

$$C = \frac{2.025}{.1} = 20.25\ \text{pF.}$$

CAPACITOR VOLTAGE RATINGS

If too much voltage is applied to a capacitor, it will distort the dielectric molecules until electrons are torn from the atoms. These free electrons flow through the dielectric from one plate to the other, destroying the action of the capacitor.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CAPACITANCE

ENERGY STORED IN A CAPACITOR

FACTORS INFLUENCING CAPACITANCE

PLATE AREA

PLATE SPACING

DIELECTRIC MATERIAL

13. The basic unit of capacitance is the farad (F or fd). Usually, it is more convenient to use a smaller unit equal to one-millionth of a farad called a ____________ (____________).

14. An even smaller unit of capacitance, only one-millionth of a microfarad, is the ____________ (____) or ________________________ (______________).

15. .00003 μF = ________ pF.

16. 1500 pF = ________ μF.

17. .00041 F = ________ μF.

18. .00027 μF = ________ pF.

19. 760 pF = ________ μF.

20. The capacitance of a capacitor accepting a charge of 2.4 coulombs when 4000 volts are applied is (a) 600F, (b) 1660F, (c) .06 μF, (d) 600 μF.

21. A 20 μF capacitor has a charge of .03 coulombs. The capacitor is charged to a voltage of (a) 1500V, (b) .0015V, (c) .00066V, (d) 6.6V.

22. What is the charge on a capacitor when its capacitance is 50 μF and the voltage between the plates is 100V? (a) 500 coulombs. (b) .5 coulombs. (c) .005 coulombs. (d) 2 coulombs.

23. How much energy is stored in a .1 μF capacitor charged to 100 volts? (a) 5 watt-seconds. (b) 5 joules. (c) .05 joules. (d) 5×10^{-4} joules.

24. Increasing the plate area of a capacitor increases its capacitance. True or False?

25. Increasing the spacing between the plates of a capacitor increases its capacitance. True or False?

26. Increasing the dielectric constant of a capacitor increases its capacitance. True or False?

27. Which of the following has the lowest dielectric constant? (a) Mica. (b) Oil. (c) Ceramic. (d) Air.

28. What is the value of a two-plate air dielectric capacitor with a plate spacing of .01 inch and plates 2 inches on a side (4 square inches)?

In some cases, this current may create enough heat to actually burn a hole through the dielectric. The amount of voltage that will produce this effect is called the "breakdown voltage" of the dielectric or capacitor. The ability of a dielectric material of a given thickness to withstand a voltage breakdown is called its **DIELECTRIC STRENGTH**. To safeguard against this type of breakdown, capacitors must be operated at voltages below the dielectric breakdown voltage. The maximum voltage that can be applied steadily to a capacitor without damage is called the **WORKING VOLTAGE** of the capacitor. This working voltage is determined by the dielectric strength and thickness of the dielectric material. Actually, the manufacturer includes a margin of safety in assigning the working voltage rating, and it usually is possible to operate a capacitor at voltages slightly higher than the specified value. However, it is best not to exceed the working voltage of the capacitor.

Dielectric strengths usually are given in kilovolts per millimeter of material thickness, with one kilovolt representing 1000 volts, and one millimeter representing .039 inch. They are not related in any definite manner to dielectric constants, and average strengths for typical materials are as follows:

Material	*Dielectric Strength kV/mm.*
Air	3
Bakelite	21
Glass	35
Mica	50
Rubber	70

When the dielectric is a solid such as waxed paper or mica, and it is punctured by excessive voltage, a permanent short circuit can occur between the plates. The capacitor then becomes worthless and must be replaced. If the dielectric is a liquid or air, a puncture still will cause a short circuit, but when the voltage is removed, the conducting path is broken up by whole molecules drifting in to occupy the damaged area in the liquid or gas, and the insulation is restored. A dielectric of this type is said to be "self-healing."

No known materials are perfect insulators. Therefore, after a capacitor is charged, there will be a small "leakage" current through the dielectric, causing the charge to "leak-off" in time. Some capacitors hold a charge for several minutes, while others retain a charge for several hours, or even months, depending on the degree of leakage.

Often, the dielectric characteristics are altered due to aging, heat and humidity. Leakage and the dielectric constant also tend to change with time. Since capacitance depends upon the dielectric constant, it also changes as time passes.

CAPACITORS IN PARALLEL

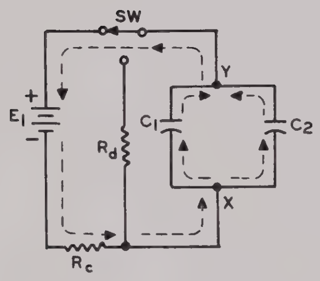


Figure 12

Capacitors are often combined in series or parallel groups to produce various values of capacitance. In the circuit of Figure 12, capacitors C_1 and C_2 are connected in parallel. Both capacitors are charged through resistor R_c and discharged through resistor R_d. The figure illustrates the charging action. Electrons leaving the negative terminal of the battery pass through resistor R_c to the point marked X. At this point, the electron flow divides. Some electrons pile up on the lower plate of C_1, while the others pile up on the lower plate of C_2. Electrons repelled from the upper plates of C_1 and C_2 flow to point Y. At point Y, electrons from both capacitors join each other to form a total electron flow which passes through switch SW to the positive battery terminal. The charging current automatically divides at point X so that the voltage across C_1 equals the voltage across C_2. When fully charged, both capacitors C_1 and C_2 will be charged to the source voltage.

IN A PARALLEL CAPACITOR ARRANGEMENT, THE TOTAL CAPACITANCE IS EQUAL TO THE SUM OF THE INDIVIDUAL CAPACITANCE VALUES.

For Figure 12 the total capacitance can be written as:

$$C_T = C_1 + C_2 \tag{4}$$

where: C_T is the total capacitance,

C_1 is the capacitance of capacitor C_1, and

C_2 is the capacitance of capacitor C_2.

If the value of C_1 is 60 μF and the value of C_2 is 40 μF, the total capacitance is equal to $C_1 + C_2 = 60 + 40 = 100$ μF. No matter how many capacitors are connected together in parallel, the total capacitance is always equal to the sum of their individual capacitance values.

CAPACITORS IN SERIES

Figure 13 shows two capacitors connected in series. With a series connection, the charging current has only one path to follow. When the capacitors stop charging, the sum of the voltages across C_1 and C_2 equals the battery voltage. As a result, each capacitor charges to a voltage which is less than the source voltage. With this arrangement, each capacitor holds less charge than if it were connected by itself across the source voltage.

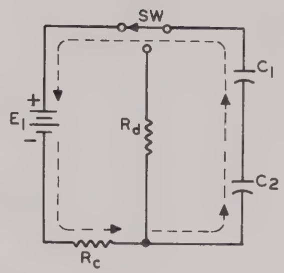


Figure 13

You can find the total capacitance of two capacitors in series as follows:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \qquad (5)$$

Notice that this method is similar to the method used when finding the total resistance of parallel resistors.

Suppose that the values of the capacitors in Figure 13 are $C_1 = 10$ μF and $C_2 = 20$ μF. Simply insert the values in the equation to find the total capacitance:

$$\frac{1}{C_T} = \frac{1}{10} + \frac{1}{20} = \frac{3}{20}$$

$$C_T = \frac{20}{3} = 6.67\ \mu\text{F}.$$

If we had four capacitors in series, the equation for finding C_T would be:

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4}$$

To use this equation, let us assume that $C_1 = 10\ \mu F$, $C_2 = 20\ \mu F$, $C_3 = 40\ \mu F$ and $C_4 = 30\ \mu F$:

$$\frac{1}{C_T} = \frac{1}{10} + \frac{1}{20} + \frac{1}{40} + \frac{1}{30}$$

To add unlike fractions, we must first find a common denominator, which in this case is 120:

$$\frac{1}{C_T} = \frac{12}{120} + \frac{6}{120} + \frac{3}{120} + \frac{4}{120} = \frac{25}{120}$$

$$C_T = \frac{120}{25} = 4.8\ \mu F.$$

When ONLY TWO CAPACITORS are connected in series, as shown in Figure 13, Equation 5 can be rearranged to form:

$$C_T = \frac{C_1 C_2}{C_1 + C_2} \qquad (6)$$

THE TOTAL CAPACITANCE FOR A SERIES CAPACITOR CIRCUIT IS CALCULATED FROM THE SAME EQUATION AS FOR THE PARALLEL RESISTOR ARRANGEMENTS.

The only difference is that here we wish to find the total series capacitance, rather than the total parallel resistance, of a circuit.

When capacitors are connected in series, the source voltage divides between them. To determine the voltage across each capacitor, we can use expressions 1b ($Q = CE$) and 1a ($E = Q/C$). To illustrate the procedure, suppose that two capacitors, $C_1 = 10\ \mu F$ and $C_2 = 20\ \mu F$, are connected in series across a 100-volt source. First, determine the total capacitance. As shown in a previous example, the total capacitance of the 10 μF and 20 μF capacitors is 6.67 μF. The total charge on the capacitors can be found from expression 1b:

$$Q = CE = 6.67 \times 10^{-6} \times 1 \times 10^{2}$$

$$= 6.67 \times 10^{-4} \text{ coulombs.}$$

Since the capacitors are connected in series, the same charge is on both capacitors. Equation 1a can be used to find the individual voltage drops:

$$E_{C_1} = Q/C$$

$$= 6.67 \times 10^{-4}/10 \times 10^{-6} = .667 \times 10^{2} \text{ volts}$$

$$= 66.7 \text{ volts.}$$

$$E_{C_2} = Q/C_2 = 6.67 \times 10^{-4}/20 \times 10^{-6} = .333 \times 10^{2} \text{ volts}$$

$$= 33.3 \text{ volts.}$$

Note that the smaller value capacitor has the larger voltage drop. Since $Q = CE$, the smaller the capacity, the greater the voltage required to obtain the same charge.

SERIES-PARALLEL CAPACITOR ARRANGEMENTS

Combining the series and the parallel capacitor groups gives us a series-parallel arrangement. Figure 14 is a circuit of this type. Capacitors C_2 and C_3 are in series. This combination is in parallel with capacitor C_1. To calculate the total capacitance: let $C_1 = 40\ \mu F$, $C_2 = 30\ \mu F$, $C_3 = 15\ \mu F$, $R_C = 10$ kΩ and $R_d = 50\Omega$.

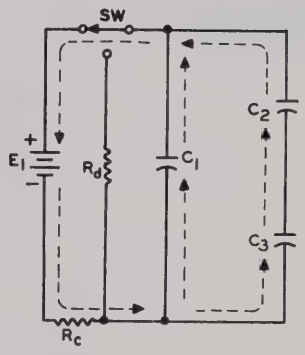


Figure 14

The capacitance in the series branch is:

$$C_{series} = \frac{C_2 C_3}{C_2 + C_3}$$

$$= \frac{30 \times 15}{30 + 15}$$

$$= \frac{450}{45} = 10\ \mu F.$$

The total circuit capacitance is:

$$C_T = C_1 + C_{series}$$

$$= 40 + 10$$

$$= 50\ \mu F.$$

TYPES OF FIXED CAPACITORS

To fulfill the different requirements in electronic equipment, many types of capacitors are manufactured. These types differ mainly in the construction of the plates and the nature of the dielectric material. Capacitors having a definite fixed value, with no provision for adjustment, are known as fixed capacitors.

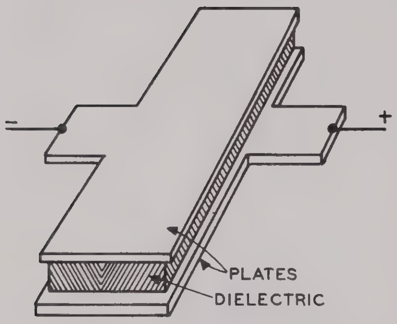


Figure 15

The basic fixed capacitor consists of two conducting plates separated by a suitable dielectric. This general plan is illustrated in Figure 15. Although it is possible to construct a capacitor in exactly this form, the physical size would have to be very large in order to produce a reasonably large capacitance value. Therefore, capacitors are rarely constructed in this manner.

Paper Type

One method of reducing the physical size and obtaining usable capacitance values is employed in the paper type capacitor, so named because the basic form includes one or more strips of waxed paper for the dielectric. Using strips of metal foil as the conducting plates, it is possible to "roll" the entire unit into a compact cylinder, as illustrated in Figure 16. Capacitors of this type are economical to manufacture, and they are available in a wide range of values.

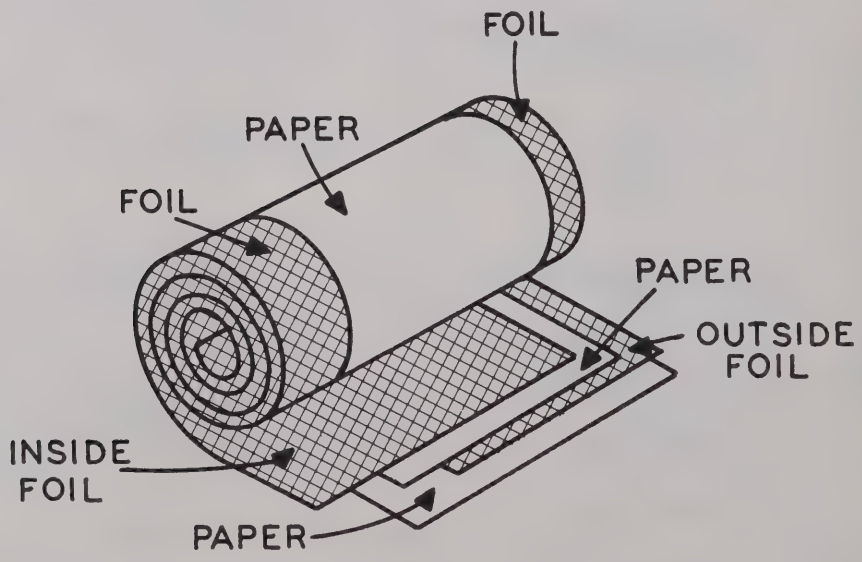


Figure 16

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CAPACITOR VOLTAGE RATINGS

CAPACITORS IN PARALLEL

CAPACITORS IN SERIES

SERIES-PARALLEL CAPACITOR ARRANGEMENTS

29. Describe the action in a capacitor when the breakdown voltage is exceeded.

30. What is the working voltage of a capacitor?

31. What factors determine the value of the working voltage?

32. How long will a capacitor hold a charge?

33. With C_1 of Figure 12 equal to .1 μF and C_2 equal to 100 μF, C_1 will charge to the voltage of E_1 before C_2. True or False?

34. Three capacitors are connected in parallel: $C_1 = 5\ \mu F$, $C_2 = 15\ \mu F$, and $C_3 = 30\ \mu F$. What is their total capacitance?

35. Write the equation for finding the total capacitance of a circuit with 5 parallel capacitors.

36. Write the equation for finding the total capacitance of three capacitors connected in series.

37. Write the simplified equation for finding the total capacitance of two capacitors connected in series.

38. When capacitors are connected in series, the charge on each capacitor is different. True or False?

39. When different value capacitors are connected in series, the voltage to which each capacitor charges is different. True or False?

40. What is the total capacitance of three capacitors in series whose values are 10 μF, 20 μF, and 60 μF?

41. Two capacitors, $C_1 = 20$ μF and $C_2 = 30$ μF, are connected in series across a 150-volt source. What is the voltage drop across each capacitor?

42. What is the total capacitance of Figure 14 if $C_1 = 20$ μF, $C_2 = 25$ μF and $C_3 = 100$ μF?

In rolling the paper and foil strips to construct the capacitor, the turns of the foil produce the same effect as the turns of an ordinary inductor. Therefore, precautions are taken to avoid inductive effects due to the "coiling" of the foil. The strips of foil are cut slightly wider than the paper, and they are staggered as illustrated in Figure 16. When the capacitor is rolled, a foil strip then protrudes from either side. The foil protruding from the side is crimped, and a connecting lead is attached to form a contact along the entire length of the foil. Wound in this manner, the capacitor is called a non-inductive type.

After the strips are rolled, the unit is enclosed in a container and sealed for protection against the harmful effects of moisture. Cardboard containers are used in many cases, with the complete unit dipped in wax for added protection. Other types use a molded plastic container, which has excellent moisture-proofing qualities as well as a certain amount of insulation against heat. These "molded paper" capacitors may be tubular in shape, or they may be flat. Still others are enclosed in metal containers; these are especially suitable for heavy duty applications.

When a rolled paper type capacitor is not enclosed in a metal container, one lead usually is designated as the outside foil. This type of capacitor will not be damaged if its leads are reversed in a circuit, but it is customary to connect the outside foil lead to the grounded side of the circuit whenever possible. As the term implies, this is the lead connected to the outer foil of the roll, and there is a shielding effect when this foil rather than the inside foil is grounded. The lead of the outer foil may be designated by a marking band, or by the word "ground" printed near one lead of the capacitor.

One serious disadvantage of the paper capacitor is the inherent weakness of the dielectric. Despite careful methods of production, wax is not uniform in structure, and the paper may have tiny flaws where breakdown may occur when voltage is applied. Once this dielectric punctures, it is useless, and the capacitor must be replaced. The dielectric strength can be increased, within limits, by using more than one strip of waxed paper between the plates (the possibility of flaws in both strips overlapping would be very remote). However, as the dielectric thickness is increased in this manner to guard against breakdown, the plates are moved farther apart, and the capacitance value is decreased. In the conventional paper capacitor, the range of available capacitance values lies between .0001 μF and 1 μF, with working voltages usually at or below 600 volts.

Improvements in the design of these paper capacitors have made it possible to increase both the range of capacitance values and the working voltages.

Many manufacturers now use an oil-impregnated paper dielectric. Some manufacturers, in addition to using more than one strip of dielectric, may include a film of impregnant between the dielectric strips to increase the dielectric strength. This material may be solid or liquid and is usually selected for its flexibility and dielectric constant. Various types of mineral oils are suitable for such applications, along with special plastics such as Mylar and Teflon.

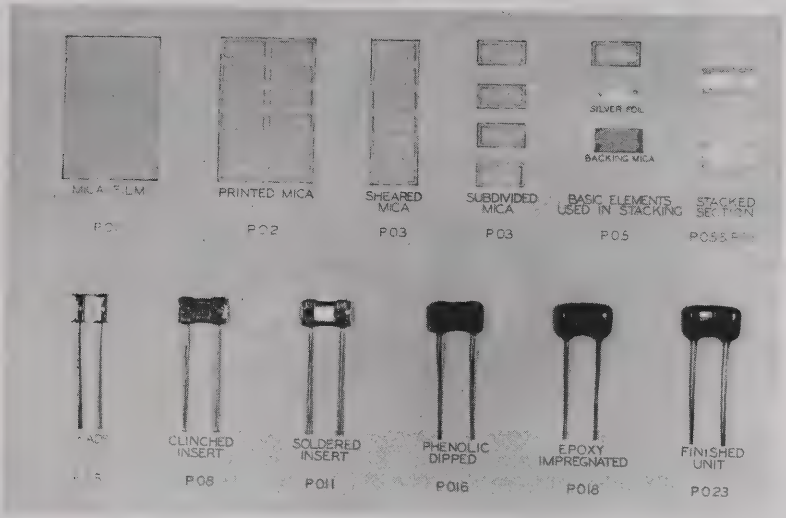
Certain capacitors are known as metallized paper capacitors, because their plates consist of thin metallic films deposited on the dielectric strip. Alternate layers of dielectric and film are "stacked," just as the alternate strips of foil and waxed paper are stacked in other paper capacitors and the complete unit is also rolled for compactness. The metal films serve as the plates, and it is possible to obtain relatively high capacitance values in very compact form with this type of arrangement.

An added advantage of the metallized paper type is its "self-healing" qualities. In an ordinary paper capacitor, arcing or breakdown of the dielectric results in carbon deposits that form permanent shorts between the plates, making the capacitor useless. With the metallized type, the metal vaporizes as soon as a breakdown occurs, and no harmful deposits form. The capacitor is usually restored to usable condition as soon as the excess voltage is removed. To illustrate the advantage of metallized construction, the voltage rating in such a capacitor may extend to 1000 volts or more, as compared to the usual maximum of 600 volts for the conventional paper type.

In some oil-filled capacitors, the oil that serves as an impregnant can also serve as the entire dielectric. Some capacitors are mounted in metal "cans," with the plates immersed in the oil dielectric. Due to the high dielectric constant and dielectric strength of the oil, it is possible to achieve relatively large capacitance and high voltage ratings. In the larger capacitors used in radio transmission and certain applications where space is not too important a factor, values up to 20 μF and 5000 working volts are not uncommon. However, physical size becomes an important factor in many applications, and other measures must be taken to achieve the desired values.

Mica Type

For use with higher voltages (usually in the better quality, lower capacitance units), thin sheets of mica or high-grade silicaglass are used for the dielectric. A particular thickness of mica can withstand a higher voltage without breaking down than can a paper dielectric. Also, mica can be split into very thin sheets while retaining its high insulating qualities. Therefore, the plates may be placed very close together, giving a high capacitance value for a specific plate size.



This photo shows the construction of a dipped mica capacitor.
Courtesy Electro Motive Mfg. Co. Inc.

In construction, alternate sheets of mica and metal foil are enclosed in a molded bakelite case. One lead is connected to every other foil sheet, and the other lead is connected to the remaining group of foil sheets, giving a number of plate sections which combine to form a large plate area. A special type, called the "silver mica capacitor," uses a film of silver deposited on the mica sheets, and ~~it generally has~~ exceptionally good stability. A stable capacitor can maintain its value within close tolerance over long periods of operation. In general, mica capacitors provide best service in a range of capacitance values from 1 pF to .1 μF, with typical working voltages up to 1000 volts or slightly higher. However, they are more expensive, so they are used generally where improved stability and voltage-handling ability are required.

Ceramic Type

Unlike some other materials, ceramic dielectrics do not deteriorate with age. Ceramic materials have a wide range of dielectric constants, which vary from 6 to over 1000, depending on the kind and quality of material used. Use of a ceramic dielectric permits the construction of very stable capacitors with high capacitance in a small sized package.

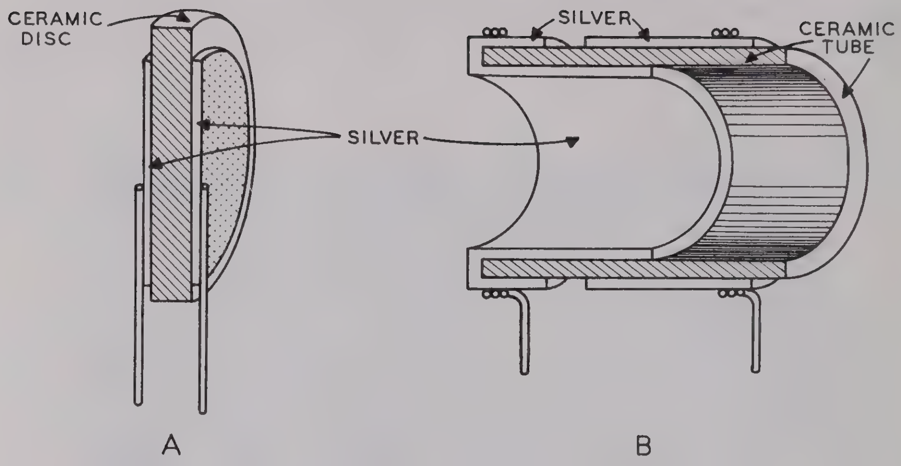


Figure 17

Figure 17 shows two popular types of ceramic capacitors. In the "disc" type of Figure 17A, a thin film of silver is deposited on each side of a small ceramic disc. Then, a short length of bare wire is soldered to each silver electrode, and the complete unit is covered with an insulating coating.

Figure 17B shows a "tubular" ceramic capacitor, in which the plates consist of silver films deposited on the inner and outer surfaces of a ceramic tube. The inner film extends around one end of the tube for a short distance on the outer surface without touching the other silver film. Electric connections to the two films are provided by wires attached near the ends of the tube. After the connecting leads are soldered to the silver films, the unit is dipped in an insulating material to form a protective coating.

Tubular ceramic capacitors are constructed with either axial or radial leads. In the axial type, the leads extend straight out from the ends, while the leads of the radial type extend at right angles to the body.

Electrolytic Type

Because of their ability to provide greater capacitance in less space, electrolytic capacitors are widely used in electronic apparatus. The main applications are in power supplies and other circuits where relatively large capacitance values at moderate working voltages are required. One type of electrolytic capacitor, known as a "wet electrolytic," is illustrated in Figure 18. In its basic form, it consists of a copper or aluminum container filled with an acid solution called the electrolyte, in which an aluminum anode is immersed.

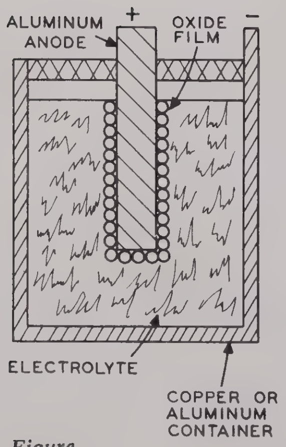


Figure 18

When this unit is connected to a dc "forming voltage" source so that the aluminum anode is positive with respect to the electrolyte, electrons move from the electrolyte solution to the anode, which serves as the positive terminal of the capacitor. Due to the electrochemical action, an oxide film, which is an electrical insulator, forms on the anode. Because of its insulating qualities, the oxide film serves as the dielectric material between the aluminum anode and the acid solution. The anode serves as one plate of the capacitor, while the electrolyte and container serve as the other plate.

The oxide film is about .00001 to .000001 inch thick in a capacitor with a 500-volt rating. In effect, there are two plates of rather large area separated by a very thin dielectric. Because capacitance is inversely proportional to the thickness of the dielectric, and the extremely thin dielectric film is formed over all the exposed surface of the anode, the capacitance obtainable per square inch of anode is very high. It is possible to construct electrolytic capacitors of large capacitance in very compact form.

The wet electrolytic is rarely used in present-day circuits because of one serious disadvantage. Since acid is used in the electrolyte, the electrolyte may spill if the unit happens to tip. To overcome this disadvantage, the "dry electrolytic" capacitor was developed. The electrolyte actually is not dry, but consists of absorbent paper or gauze saturated with electrolyte solution.

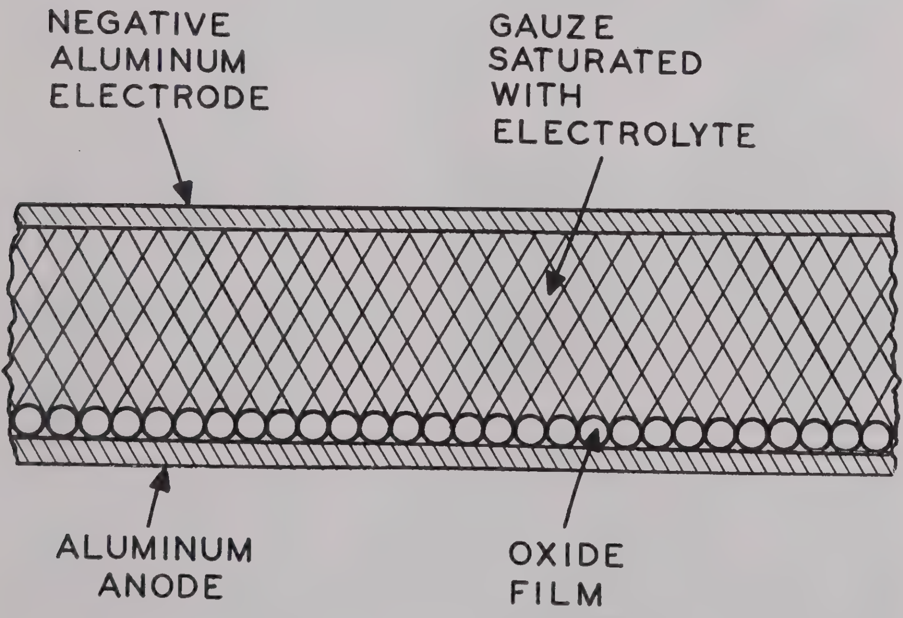


Figure 19

The nature of construction is shown in the cross-sectional diagram of Figure 19. A strip of aluminum foil is placed on either side of the gauze. A "forming" voltage is applied, and the oxide film dielectric forms on the foil strip connected to the positive terminal of the source. In commercially manufactured dry electrolytics, the foil and gauze strips usually are rolled in the same manner as the rolled paper capacitor and then enclosed in a cardboard or metal container.

More than one electrolytic capacitor in a single container is possible using the process illustrated in the cross section of Figure 20A. The foil strips are split into sections, with each section serving as the anode for an individual capacitor unit. A separate lead is connected to each of these strips, and a single "common" lead serves as the negative terminal for each section. This is a valuable space saver, since a single "multi-section" capacitor can be used in place of several individual units.

To identify the sections in a multi-section electrolytic capacitor of this type, the manufacturer may use colored leads, with each section's capacitance value and its corresponding lead color indicated on the body of the capacitor.

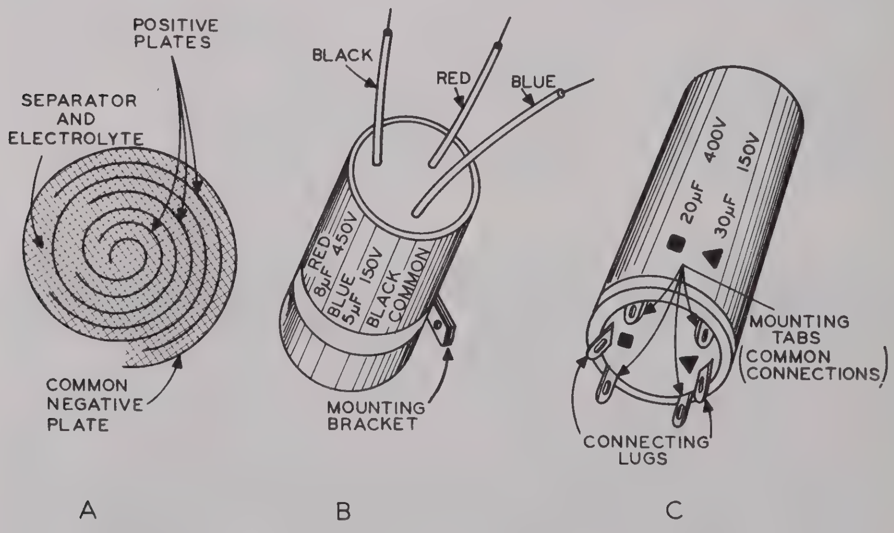


Figure 20

When terminals or connecting lugs are used instead of wire leads, a special symbol may be assigned to each terminal, and the symbols and corresponding capacitance values once again are indicated on the container. These methods of identification are illustrated in Figures 20B and 20C.

In a metal-cased electrolytic of Figure 20C, the common negative terminal is internally connected to the metal case, and the mounting lugs form the negative connecting point. Special mounting plates usually are supplied with these metal "can" electrolytics, and the mounting lugs fit into corresponding slits on the plate for convenience in mounting. The plate is riveted or screwed to the chassis over a suitable cutout, and the capacitor can is inserted and secured. The container, serving as the common negative terminal, then forms an electrical contact with the chassis.

If for some reason this contact is not desired, the manufacturer supplies an alternate mounting plate made of fiber so that the container is insulated from the chassis. A wired connection then can be made to the mounting lugs protruding from the underside of the plate.

Electrolytic capacitors are polarized; that is, the aluminum anode always must be connected to the positive terminal of the circuit. If the connections are reversed, the flow of electrons from the aluminum anode through the film to the electrolyte will be large enough to cause damaging heat. Also, the common types of electrolytic capacitors cannot be used in alternating current circuits, due to the reversals of polarity. Most electrolytic capacitors are used in dc or pulsating dc circuits with applied voltages of less than 600 volts. Capacitance values may range up to 1000 μF or higher.

Unfortunately, the oxide film tends to disappear if an electrolytic capacitor is not used for a long period of time. Although the film forms again if a voltage is applied, permanent damage sometimes occurs before this very thin film develops enough to prevent damaging current. For this reason, a unit may break down when first turned on after being out of use for a long period of time. Electrolytics that have been in storage should be "reformed," by connecting them to a low-voltage source until the film has had time to build up.

The dry electrolytic capacitor is often too bulky for many miniature circuits. Tantalum capacitors can provide even greater capacitance in a smaller unit. These types of capacitors employ tantalum, a metallic chemical element, as the plates with tantalum pentoxide as the dielectric. In addition to small size, tantalum capacitors are much more stable than electrolytic capacitors. They do have working voltage limitations with 150 volts being a common maximum value.

The capacitors shown employ a solid tantalum dielectric. The use of this material permits high capacitance with small size.

Courtesy Sangamo Electric Co.

TYPES OF VARIABLE CAPACITORS

In some circuits, it is necessary to vary or adjust the capacitance for proper operation. A device or component designed for this purpose is known as a **VARIABLE CAPACITOR**. We know that capacitance can be changed by varying either the effective plate area, the spacing between the plates, or the dielectric material; one of these three methods is employed in every variable capacitor.

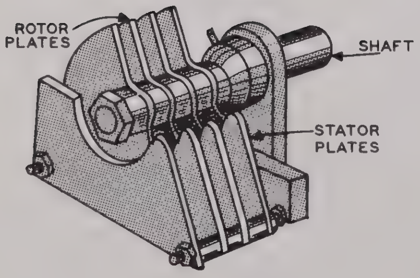


Figure 21

Movable Plate Type

The first and most common method is illustrated in Figure 21. Known as a movable plate type of variable capacitor, it is made up of two sets or groups of plates. One group of plates is called the **STATOR**. This stator is insulated from, but held stationary by, the frame. The plates are electrically connected by metal spacers which also hold them the proper distance apart.

The other group of plates, known as the **ROTOR**, is fastened to a movable shaft which is insulated from the stator. By turning the shaft, the rotor plates move in between the stator plates and, by changing the area of the plates actually intermeshed, the capacitance is varied.

Even when the rotor plates are turned out as far as they will go, some capacitance still is present due to the close position of the rotor and stator. For this reason, variable capacitors are rated as to both their "maximum" and "minimum" capacitance. For example, a typical tuning capacitor for a broadcast receiver might have a capacitance range of 10 to 365 pF. This means that it would provide a variation of capacitance between 10 pF and 365 pF as it is turned from one extreme of rotation to the other.

In many applications it is desirable to change the capacitance simultaneously in more than one section of the circuit by varying a single shaft. This may be done by mounting more than one set of rotor and stator plates so that all rotors are turned by the single shaft. When constructed in this way, the tuning capacitor is said to be "ganged," with each complete rotor and stator set representing one "gang" of the unit.

Movable Dielectric Type

A type of variable capacitor operating on the principle of changing the dielectric material is illustrated in Figure 22. A nonsymmetrical piece of bakelite moves between two fixed plates. Due to the shape of the dielectric piece, more or less of the material is inserted between the plates as the shaft is rotated. Since bakelite has a higher dielectric constant than air, the capacitance increases as a greater amount of dielectric moves between the plates, and the capacitance decreases as the dielectric material is withdrawn.

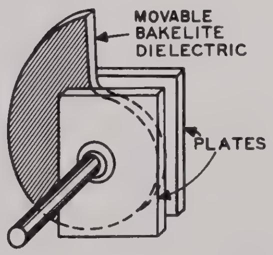


Figure 22

Pressure Type

The capacitance also may be varied by changing the distance between the plates, a principle used in the pressure type variable capacitor of Figure 23. Made of spring metal, the upper plate in this arrangement has a tendency to move away from the lower plate. The screw adjustment varies the pressure on this upper plate, causing it to move nearer to or farther from the lower plate.

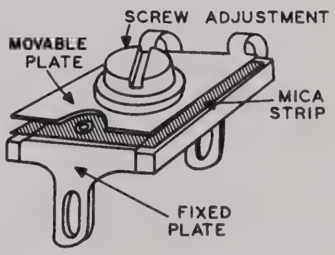


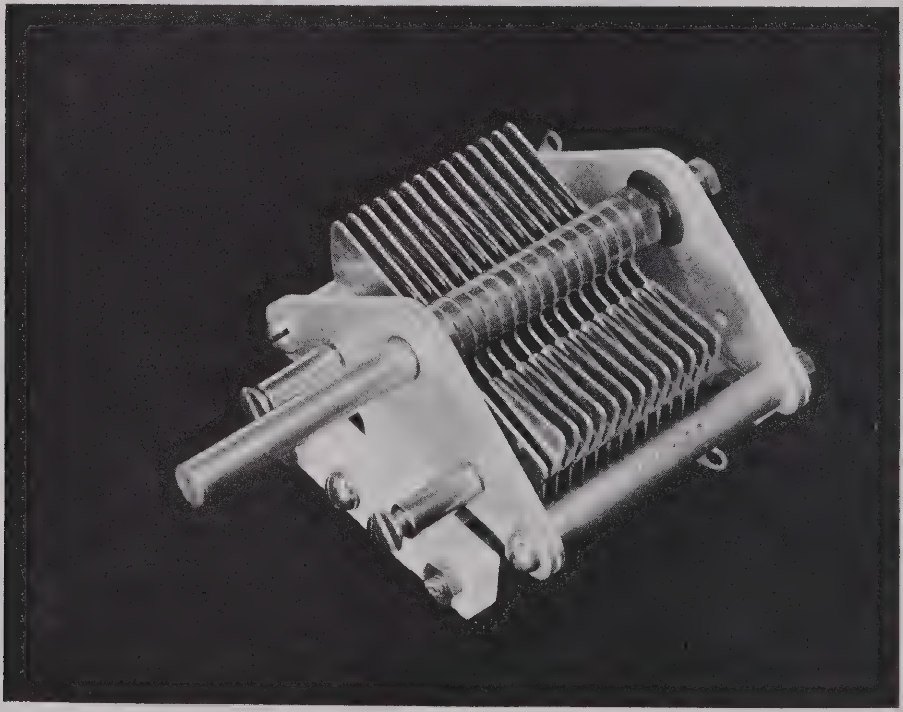
Figure 23

If the screw is turned in the clockwise direction, the upper plate moves closer to the lower plate and the capacitance increases. If the screw is turned in the opposite direction, the pressure on the upper plate decreases, the spring action causes it to move farther from the lower plate, and the capacitance decreases.

The dielectric between the two plates consists of sheets of mica or other suitable materials. Units of this type usually are adjusted to a certain value and left at that value, rather than continually varied, as in the case of a tuning capacitor.

TEMPERATURE COEFFICIENT

For a number of years, manufacturers have produced small capacitors of great stability, that have definite changes of capacitance with temperature changes in either a positive or negative direction, as desired. This change of capacitance due to temperature changes is known as the **TEMPERATURE COEFFICIENT (T.C.)**, and is expressed as the change of capacitance per unit capacitance per degree Celsius. (Celsius was the inventor of the centi-



The above photo shows a typical air dielectric variable capacitor. Units of this type are widely employed in high-frequency applications.
Courtesy National Co., Inc.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TYPES OF FIXED CAPACITORS

PAPER TYPE

MICA TYPE

CERAMIC TYPE

ELECTROLYTIC TYPE

TYPES OF VARIABLE CAPACITORS

MOVABLE PLATE TYPE

MOVABLE DIELECTRIC TYPE

PRESSURE TYPE

43. Capacitors that have no provision for adjustment are called ________.

44. Capacitors are not usually constructed of two flat plates separated by a dielectric. Why are other construction methods used?

45. For a dielectric, a paper type capacitor uses (a) metal foil, (b) wax, (c) thin plastic, (d) waxed paper.

46. For its conducting plates, a metallized paper capacitor uses (a) a film of metal, (b) metal foil, (c) metal plates.

47. A silver mica capacitor is constructed of alternate sheets of mica and metal foil. True or False?

48. The ceramic material used in ceramic capacitors has a (a) high dielectric constant, (b) low dielectric constant.

49. Mica and ceramic capacitors generally share the property of (a) low stability, (b) high stability.

50. The dielectric of an electrolytic capacitor is an oxide film on the negative electrode. True or False?

51. If you do not want the common connection of a metal "can" electrolytic capacitor to connect to the chassis, what method of mounting should be used?

52. Electrolytics differ from other capacitors because they (a) have higher voltage ratings, (b) are polarized, (c) are less easily damaged.

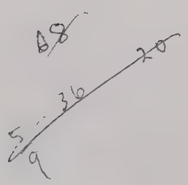
53. Why would an electrolytic capacitor require connection to a low-voltage source before operation?

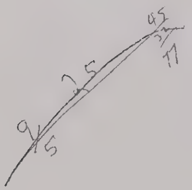
54. Although dry electrolytic capacitors have a higher maximum working voltage limit, tantalum capacitors provide ___________ capacitance for unit size.

55. In what three ways may the capacity of variable capacitors be changed?

56. In the movable plate type of variable capacitor, which set of plates is insulated from the frame and shaft?

57. A typical value of minimum capacitance for a movable plate capacitor is (a) 10 pF, (b) 50 pF, (c) 150 pF, (d) 365 pF.





grade thermometer which has 100 degrees between the freezing and the boiling points of water. Temperatures formerly were specified as degrees Centigrade on this scale, but the name Celsius has been substituted recently to honor the inventor.) The change is usually designated in parts per million per degree Celsius (ppm/°C). If the temperature coefficient is positive, the capacitance varies in the same direction as the temperature change; that is, an increase in temperature causes an increase in capacitance and a decrease in temperature causes a decrease in capacitance. If the temperature coefficient is negative, an increase in temperature produces a decrease in capacitance and a decrease in temperature causes an increase in capacitance.

The standard for these temperature comparisons is 25° Celsius (room temperature), and the ratings are based on this value. Using the known capacitance, temperature coefficient and temperature change, the total capacitance change for any capacitor is given by the equation:

$$\Delta C = \frac{\text{T.C.} \times C \times t}{1{,}000{,}000} \qquad (7)$$

where: ΔC (called delta C) is the capacitance change in pF,

T.C. is the temperature coefficient in ppm/°C,

C is the capacitance in pF, and

t is the temperature change in degrees Celsius.

For example, suppose that a 100 pF capacitor with a temperature coefficient of —30 ppm/°C is operating at a temperature of 26° Celsius. The capacitance change produced by the one-degree rise in temperature is:

$$C = \frac{-30 \times 100 \times 1}{1{,}000{,}000} = -.003 \text{ pF.}$$

The actual capacitance at the new temperature is 100 — .003, or 99.997 pF. If the temperature were decreased instead of increased by one degree, the new capacitance would be 100 + .003, or 100.003 pF.

CAPACITOR COLOR CODES

To identify the capacitance quickly, many small fixed capacitors are color coded by small dots or spots of paint. In designating the actual capacitance, the numbers represented by these colors are the same as those used in the resistor color code. The main difference is that resistors are color-coded to designate ohms, while capacitor color codes designate picofarads. Sometimes other characteristics besides the capacitance are indicated, and a number of color code systems for capacitors have been developed through the years. The main difference between the many arrangements is in the amount of information included.

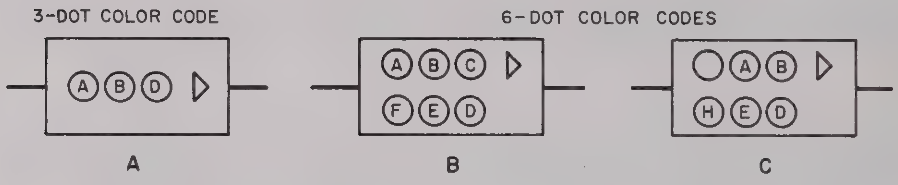


Figure 24

Two of the early codes (still in limited use for mica capacitors) are shown in Figures 24A and 24B. The 3-dot system of Figure 24A is used with capacitors having a working voltage rating of 500 volts and a 20% capacitance tolerance. The color dots have the values given in Figure 25, and are read in the order A, B, D, to give the capacitance in picofarads. To read the code, the capacitor first is turned so that any printing, such as the manufacturer's name, appears right side up. If the capacitor has an arrow embossed on its body, the arrow must point from left to right, or if the dots are pointed, they must point to the right.

The first dot represents the first number in the capacitance value, the second dot represents the second number, and the third dot represents the decimal multiplier by which the first two numbers are multiplied to obtain the capacitance in picofarads. For example, suppose that dot A of Figure 24A is brown, B is black and D is red. From the table of Figure 25, brown is 1, black is 0 and red is ×100. The first two digits are written as a single number and multiplied by the decimal multiplier. In this example, the capacitance is 10 × 100, or 1000 picofarads. To convert this value to microfarads, the decimal point can be moved six places to the left, to give a capacitance of .001 microfarad.

The 6-dot system of Figure 24B not only expresses the capacitance to three significant figures but, in addition, indicates the tolerance and voltage rating. Holding the capacitor in the same position as described for the 3-dot system, the dots are read in the order A, B, C, D, E, F. The dots of the top row, reading in order from left to right, represent the first three numbers of the

MICA & MOLDED PAPER CAPACITOR COLOR CODE

COLOR	SIGNIFICANT FIGURE			DECIMAL MULTIPLIER	TOLERANCE		DC VOLTAGE	
					MICA	PAPER		
	A	B	C	D	E	E	F	G
BLACK	0	0	0	1	20%	20%	0	0
BROWN	1	1	1	10	—	—	1	1
RED	2	2	2	100	2%	—	2	2
ORANGE	3	3	3	1000	3%	30%	3	3
YELLOW	4	4	4	10,000	—	40%	4	4
GREEN	5	5	5	100,000	5%	5%	5	5
BLUE	6	6	6	1,000,000	—	—	6	6
VIOLET	7	7	7	10,000,000	—	—	7	7
GRAY	8	8	8	100,000,000	—	—	8	8
WHITE	9	9	9	1,000,000,000	—	10%	9	9
GOLD	—	—	—	.1	5%	—	—	—
SILVER	—	—	—	.01	10%	—	—	—
NONE	—	—	—	—	20%	—	—	—

Figure 25

225 000

capacitance value. In the bottom row, the dots are read from right to left to give the decimal multiplier, the tolerance and the voltage rating.

To illustrate this system, assume that the dot colors are: A-red, B-red, C-green, D-orange, E-gold, and F-blue. By using the system just described, a 225,000 pF capacitor, with a tolerance of 5% and a voltage rating of 600 volts, is indicated. (The color code gives a single-digit number to which two zeros are added to obtain the voltage rating.)

In the current standard capacitor color code, shown in Figure 24C, dots A, B and D indicate the capacitance, and dot E the tolerance. The unlettered dot at the upper left designates whether the capacitor meets the Electronics Industries Association (EIA) or the Joint Army and Navy (JAN) specifications. The EIA code uses a white dot, while the JAN code employs a black dot. There is no working voltage given in the code, and the EIA and JAN specifications must be consulted to determine the voltage rating for a given capacitance value, as well as other characteristics of the capacitor. Dot H is used by the manufacturer to indicate some feature of the capacitor that a particular buyer requires in his equipment. For instance, the dot may mean the capacitor must withstand a temperature of 160°C. Unless the manufacturer's specifications are available, there is no way of determining the meaning of this dot.

To illustrate the use of this color code, assume that the dot colors are as follows: A-red, B-green, D-red, E-silver, H-black. Also, assume that the unlettered dot is black, indicating JAN. From the table of Figure 25, the capacitance is found to be 2500 pF ± 10%. Unless a manufacturer's list of classes and corresponding characteristics is at hand, dot H may be disregarded.

The coding system of Figure 24C is very similar to the coding of Figure 24B. If the upper left dot is white or black, there may be some uncertainty as to which system of coding has been used. If the capacitor in question happens to be mounted in a circuit, a diagram listing parts values for that circuit may be available for positive identification. Also, if all other capacitors in that circuit have either a black or a white dot in the upper left position, chances are that the system of Figure 24C is used. If dots of other colors appear in the upper left corner, the system of Figure 24B probably is used. Since the code of Figure 24B is being replaced by that of Figure 24C, capacitors of recent manufacture will more than likely be coded according to Figure 24C, while older capacitors will probably use the coding of Figure 24A. In general, the coding of Figure 24C may be assumed unless there is reason to believe that some other type of coding has been used.

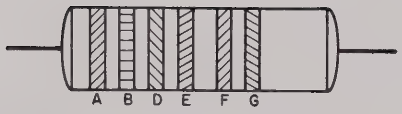


Figure 26

Some manufacturers mark color codes on molded paper capacitors, as shown in Figure 26. For the tubular type, the color code shown in Figure 25 is used. Color bands A, B and D indicate the capacitance, band E the tolerance, and bands F and G the voltage rating. For example, in Figure 26, a capacitor on which the band colors are A-brown, B-green, D-red, E-black, F-brown and G-blue has a capacitance of 1500 pF, a tolerance of 20%, and a voltage rating of 1600 volts. Voltage ratings are identified by a single-digit number (one color band) for ratings up to 900 volts, and by a two-digit number (two color bands) for ratings above 900 volts. To complete the voltage rating, two zeros are placed after the digit or digits indicated by the color code. In this example, the two color bands indicate 16, which is then read as 1600 volts.

The color code on ceramic capacitors is shown by color bands or spots. For axial lead capacitors, the arrangement of Figure 27A is employed. Figure 28 shows the ceramic capacitor color code. Although similar in appearance to the tubular molded paper capacitors which also use a band code, the axial type ceramics usually can be identified by their smaller size and lesser number of bands. Also, the bands usually are wider on the ceramic than on the molded paper type. With the unit in the position shown, the color bands are read in the order B, C, D and E. Bands B and C indicate the first two significant figures, D the decimal multiplier, and E the tolerance.

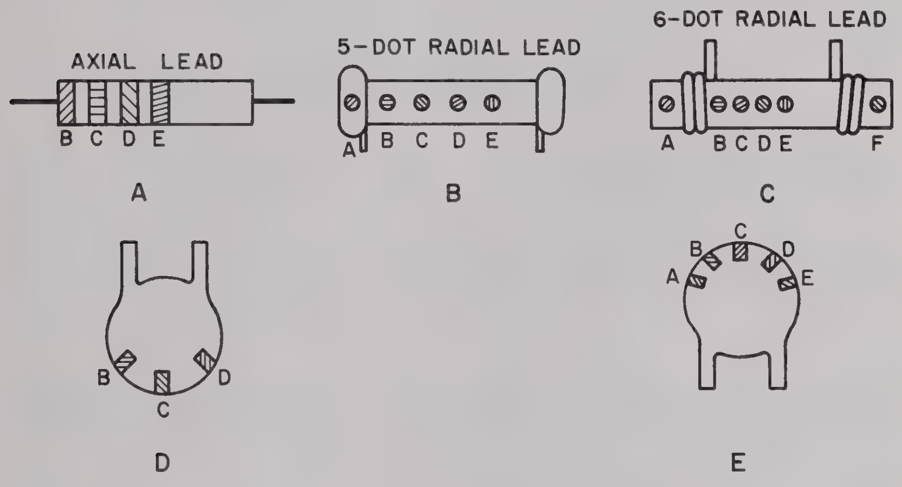


Figure 27

Capacitors using this code are manufactured with a standard voltage rating of 500 volts, so no band is necessary for working voltage. If the capacitance is 10 pF or less, the tolerance is expressed in picofarads (micromicrofarads), and is taken from the left hand E column. If the capacitance is greater than 10 pF, the tolerance is expressed as a percentage, and is taken from the right hand E column. With one exception, the tolerance values indicate that the actual value may be either above or below the coded value. The exception is in the case of a capacitance over 10 pF where the E band is blue, which means the capacitance may be up to 100% above the coded value, but never below the rated value.

To illustrate the use of the code, assume that the color bands of a capacitor are as follows: B-black, C-green, D-black and E-white. According to Figure 28, the capacitance is 5 pF. Since this is smaller than 10 pF, the tolerance is taken from the left E column, where a white band corresponds to a tolerance of ±1 pF.

Radial lead capacitors may be coded according to the 5-dot system shown in Figure 27B, or the 6-dot system shown in Figure 27C. Except for color spot F in Figure 27C, the two systems are identical, with the color spots read in the order A, B, C, D, E and F. In both systems, color spot A represents the temperature coefficient listed in column A of Figure 28. As indicated in this column, the white color can represent any coefficient between —330 and

+750, and if a white band or dot is used, specifications must be obtained from the manufacturer to determine the exact coefficient. Also, a silver band or dot shows that the temperature coefficient is too high for practical use in any critical circuits, and the capacitor is suitable only for circuits where a relatively large change in capacitance will not prevent normal operation. Color spots B and C represent the first two digits of the capacitance value, and spot D represents the decimal multiplier. The tolerance rating is given by spot E.

CERAMIC CAPACITOR COLOR CODE

COLOR	TEMPERATURE COEFFICIENT PPM / °C	SIGNIFICANT FIGURE		DECIMAL MULTIPLIER	TOLERANCE		DC VOLT
					10 pF OR LESS	OVER 10 pF	
	A	B	C	D	E	E	F
BLACK	0	0	0	1	2 pF	20 %	—
BROWN	− 30	1	1	10	.1 pF	1 %	150
RED	− 80	2	2	100	—	2 %	—
ORANGE	− 150	3	3	1000	—	2.5 %	350
YELLOW	− 220	4	4	10,000	—	—	—
GREEN	− 330	5	5	—	.5 pF	5 %	500
BLUE	− 470	6	6	—	—	+100% −0%	—
VIOLET	− 750	7	7	—	—	—	—
GRAY	+ 30	8	8	.01	.25 pF	—	—
WHITE	−330 TO +750	9	9	.1	1 pF	10 %	—
GOLD	+ 100	—	—	—	—	—	—
SILVER	NOT RATED	—	—	—	—	—	—

Figure 28

Radial lead capacitors of the type shown in Figure 27B are manufactured with a standard 600-volt rating and, therefore, do not require a voltage rating color code. Conversely, capacitors of the type shown in Figure 27C are manufactured in a number of different voltage ratings, and color dot F is added. For Figure 27C, a 150-volt rating is indicated by a brown spot at F, a 350-volt rating by an orange spot, and a 500-volt rating by a green spot. If spot F is omitted, the voltage rating is 500, the same as the green spot.

The standard color codes for flat, disc-type ceramic capacitors are shown in Figures 27D and 27E. For the three-dot code, point the leads upward as in Figure 27D. Dots B and C refer to columns B and C of Figure 28, and dot D gives the decimal multiplier of column D. A tolerance of 20% is assumed. For the five-dot code, point the leads downward, as in Figure 27E. From left to right, the dots represent the temperature coefficient, the first two digits of the capacitance, the decimal multiplier and the tolerance. A working voltage of 500 volts is assumed for both codes.

Some three-dot ceramics are coded the reverse of Figure 27D. If the manufacturer's coding system is not known, and if the standard code does not yield a logical value, read the dots from right to left; that is, consider dot B to be on the right, and dot D on the left. In some cases, the value is printed on a disc ceramic capacitor, and no color code is used.

Figure 30 at the end of the lesson shows several examples of mica, molded and ceramic capacitors. The corresponding values are shown in Figure 31.

CAPACITOR SYMBOLS

The basic schematic symbol for a fixed capacitor was first shown in Figure 5A. The curved plate in this symbol designates the plate that connects toward the grounded side of the circuit, which is the outside foil lead in the case of a rolled paper type capacitor. An electrolytic capacitor has the same basic symbol, but polarity marks are added, as shown in Figure 29A.

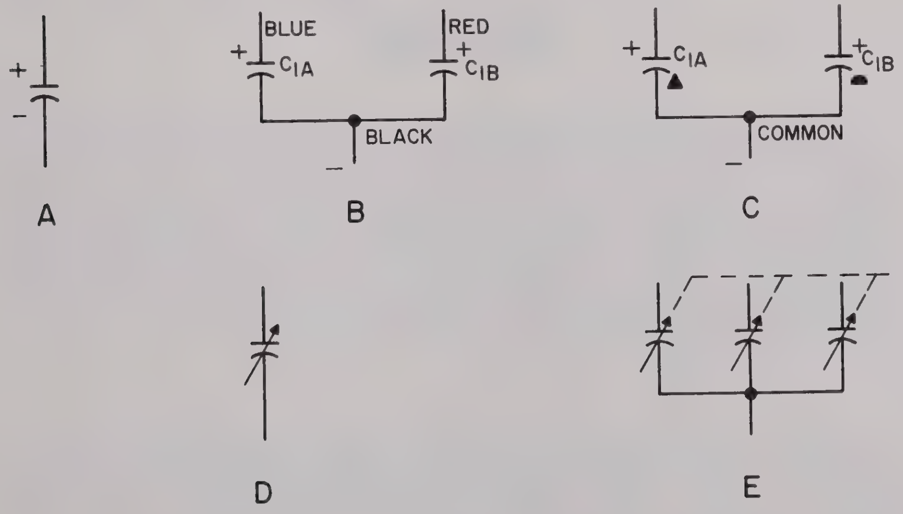


Figure 29

With multi-section electrolytic capacitors, some method of distinguishing between the sections is included; the most common methods are illustrated in Figures 29B and 29C. If the unit has colored leads, the lead colors are specified. If code symbols are included on the capacitor can, these markings are entered near the schematic symbol. To aid in identifying the sections, a letter may be added to the subscript. For example, if a two-section electrolytic is identified as C_1 in a schematic, one section might be labeled C_{1A}, and the other C_{1B}. This is strictly a matter of convenience, making it possible to distinguish one section from another in any accompanying literature.

The symbol for a variable capacitor shown in Figure 29D differs from that of the fixed capacitor only by the addition of a slanted arrow. This arrow means that the capacitor is varied by one of the methods previously explained. If more than one unit is varied simultaneously by a single shaft, as in the case of a ganged tuning capacitor, the arrows for each section are joined by dashed lines, as illustrated in Figure 29E. Although the symbols are pretty well standardized, slight variations may be found in the diagrams put out by different equipment manufacturers. However, these variations will be minor, and the symbols should be readily identified. One of the primary applications of the capacitor is that of filtering, based on the ability of the capacitor to block dc and pass ac. In the next lesson, the subject of power supplies will be considered, and the use of the capacitor and its properties of storing energy will be further explained. Also, later lessons will describe the many other applications of the capacitor which make it such an important unit in the field of electronics.

SUMMARY

Capacitance plays an important part in the electrical and electronic fields. In its simplest form, a capacitor consists of two conductive plates separated by a dielectric. The capacitance of a capacitor varies directly with the size of the plates and the dielectric constant, and inversely with the spacing between the plates. This means that increasing the plate area or using a dielectric with a higher dielectric constant increases the capacitance of the unit. Decreasing the spacing between the plates also increases the capacitance.

The electrical characteristics of a capacitor can be described in terms of capacitance, tolerance, voltage rating and temperature coefficient. Capacitors come in many different shapes and sizes due to the different types of construction, characteristics and use.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TEMPERATURE COEFFICIENT

CAPACITOR COLOR CODES

CAPACITOR SYMBOLS

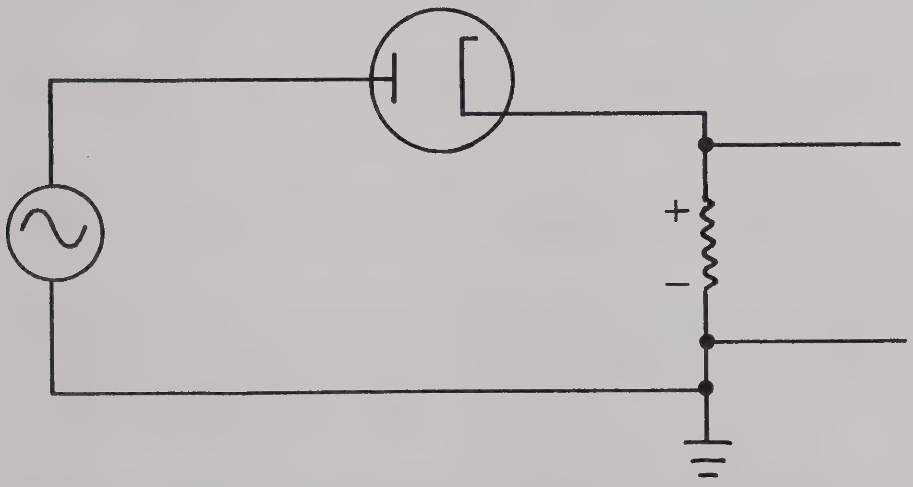
58. In regard to capacitors, what is meant by a positive temperature coefficient?

59. What is the actual capacitance of a capacitor rated at 250 pF with a temperature coefficient of —40 ppm/°C when operated at a temperature of 22° Celsius?

60. Suppose that a 6-dot mica capacitor corresponding to Figure 24C is color coded white, yellow, violet in the top row and black, silver, red on the bottom row. What are the capacitance and tolerance ratings of this capacitor?

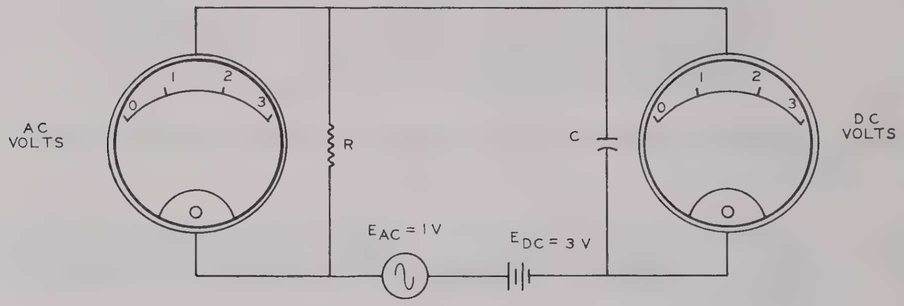
61. Is the capacitor in Practice Exercise 60 an EIA or JAN unit?

62. Add an electrolytic capacitor across the resistor in this diagram.

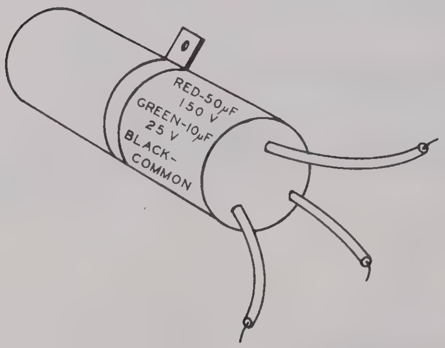


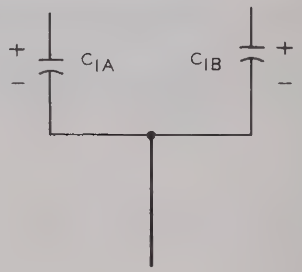
63. Draw a symbol for a two-gang variable tuning capacitor.

64. An ac generator and dc battery combine to serve as the voltage source in the circuit below. Appropriate meters are connected to indicate the voltage across the resistor and the capacitor. Draw in the pointers for the meters, indicating the voltages that appear across the resistor and capacitor. Assume that the capacitor offers no resistance at all to ac in this example.



65. C_1 is the dual electrolytic capacitor shown at the left. Using either section for C_{1A} or C_{1B}, indicate the lead colors and corresponding capacitance values in the schematic symbol.





IMPORTANT DEFINITIONS

CAPACITANCE — The property of a capacitor that determines the quantity of electric energy that it can store.

CAPACITOR — A device consisting of two conducting surfaces separated by an insulator and having the ability of storing electric energy. Also called a condenser.

CHARGE — The number of electrons held on the capacitor plates. The act of forcing electrons onto the capacitor plates.

CHARGED — The condition of a capacitor which has the full charge it can receive from a given applied voltage.

DIELECTRIC — The insulating material between the plates of a capacitor.

DIELECTRIC CONSTANT (k) — The property of the dielectric material that determines how much electric energy can be stored in a capacitor of a particular size by a value of applied voltage.

DIELECTRIC STRENGTH — The ability of a dielectric material of specified thickness to withstand high voltages without breaking down.

DISCHARGED — The removal of the charge in a capacitor by completing a circuit between the plates.

DISPLACEMENT CURRENT — The current that flows in a circuit containing a capacitor whenever the capacitor charges or discharges.

ELECTRIC FIELD — A field of force that exists between positively and negatively charged surfaces. In a capacitor, the field is assumed to consist of lines of force which extend through the dielectric from the positive to the negative plate.

FARAD (F) — The unit of measure for capacitance. It is the capacitance of a capacitor in which an applied voltage of one volt will store a charge of one coulomb. The more practical units of capacitance are the microfarad and picofarad (micromicrofarad).

PLATES — In a capacitor, the plates are the conducting surfaces.

IMPORTANT DEFINITIONS (Continued)

ROTOR — The movable group of plates of a variable capacitor.

STATOR — The stationary group of plates of a variable capacitor.

TEMPERATURE COEFFICIENT (T.C.) — In a capacitor, the rating which determines the change in capacitance corresponding to a given change in operating temperature. It is usually expressed as the change in capacitance per unit of capacitance per degree Celsius.

VARIABLE CAPACITOR — A capacitor in which the capacitance can be varied by some mechanical means.

WORKING VOLTAGE (WV) — The maximum voltage that may be applied continuously to a capacitor without risking breakdown.

ESSENTIAL SYMBOLS AND EQUATIONS

T.C.	Temperature coefficient (parts per million/°C)
ΔC	Change in capacitance (picofarads)
d	Plate spacing in inches
t	Change in temperature (degrees Celsius)
A	Plate area in square inches
C	Capacitance (farads)
C_1	Capacitance of capacitor C_1 (farads)
C_2	Capacitance of capacitor C_2 (farads)
C_T	Total capacitance (farads)
E_n	Energy (joules or watt-seconds)
E	Potential difference (volts)
k	Dielectric constant
Q	Charge (coulombs)

$$C = \frac{Q}{E} \tag{1}$$

$$E = \frac{Q}{C} \tag{1a}$$

$$Q = CE \tag{1b}$$

ESSENTIAL SYMBOLS AND EQUATIONS
(Continued)

$$E_n = \frac{CE^2}{2} \qquad (2)$$

$$C = \frac{0.225\ kA}{d} \qquad (3)$$

$$C_T = C_1 + C_2 \qquad (4)$$

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} \qquad (5)$$

$$C_T = \frac{C_1C_2}{C_1 + C_2} \qquad (6)$$

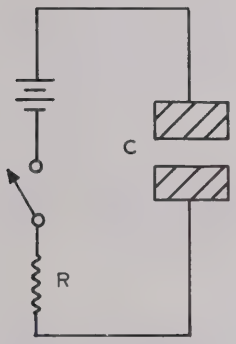
$$\Delta C = \frac{T.C. \times C \times t}{1{,}000{,}000} \qquad (7)$$

PRACTICE EXERCISE SOLUTIONS

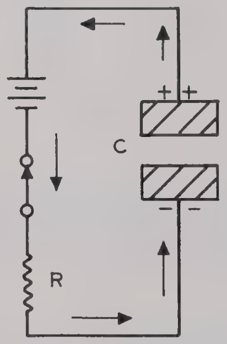
1. plates; dielectric

2. to store electric energy

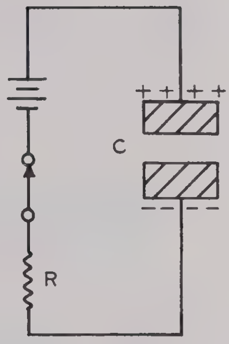
3. True — The dielectric can be any good insulator.



A



B



C

4. In diagram A, electron flow is zero because the switch is open, and it is zero in diagram C because once the capacitor is fully charged (equal to the battery voltage) it will accept no additional electrons. Therefore, no current direction arrows are shown in diagrams A and C. The charge on the capacitor plates of diagram A is zero, so + and — signs are not shown. A charge is indicated in diagram B by two + and two — signs. A greater charge is indicated in diagram C by means of four + and four — signs.

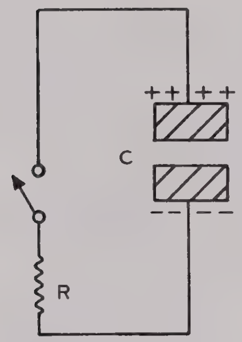
5. If the battery voltage were increased, the capacitor would increase its charge until it was again equal to the battery voltage.

6. True — A dielectric is an insulator.

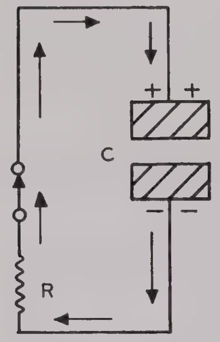
7. True — In fact, it can exist only in an insulator, because a conductor would provide a path for electron flow across the field (also called a "short" or "short circuit"). An electric field can be present in the dielectric between two capacitor plates, but there is no field within each plate.

8. False — Current can exist in the circuit during both the charge and the discharge periods.

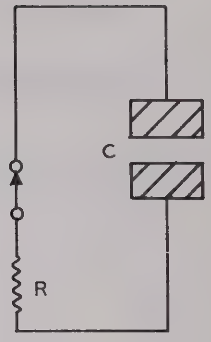
PRACTICE EXERCISE SOLUTIONS (Continued)



A



B



C

9. No current flows and no arrows are shown in diagrams A and C. The direction of the arrows in diagram B during discharge are the reverse of those shown during charge in diagram B of Question 4.

10. passes; blocks — We know that current can exist in a capacitor circuit during the charge and discharge periods. Current will always be present if the applied voltage alternates faster than the charge or discharge rate. In a dc circuit, current will be blocked once the capacitor is fully charged.

11. (c) pulsating dc.

12. False — The capacitor will continue to charge and discharge to follow the ac component of the pulsating dc voltage.

13. microfarad (μF or mfd)

14. picofarad (pF); micromicrofarad ($\mu\mu$F or mmF)

15. 30

16. .0015

17. 410

18. 270

19. .00076

PRACTICE EXERCISE SOLUTIONS (Continued)

20. (d) 600 μF. — $C = Q/E = 2.4/4 \times 10^3 = 6 \times 10^{-4}F = 600\ \mu F$.

21. (a) 1500V. — $E = Q/C = 3 \times 10^{-2}/2 \times 10^{-5} = 1.5 \times 10^3 = 1500$ volts.

    (Note: $20\ \mu F = 2 \times 10^{-5}F$. This conversion is necessary since C in the equation is in basic units of farads.)

22. (c) .005 coulombs. — $Q = CE = 5 \times 10^{-5} \times 1 \times 10^2 = 5 \times 10^{-3} =$ .005 coulombs.

23. (d) 5×10^{-4} joules.—

$$E_n = \frac{CE^2}{2} = \frac{.1 \times 10^{-6}\,(1 \times 10^2)^2}{2} = \frac{.1 \times 10^{-6} \times 1 \times 10^4}{2}$$

$$= \frac{.1 \times 10^{-2}}{2} = .05 \times 10^{-2} \text{ or } 5 \times 10^{-4} \text{ joules or watt-seconds.}$$

24. True — A larger plate area allows more electrons to accumulate on one plate, and more can be removed from the other plate.

25. False — The repelling or attracting properties of electric charges vary inversely as the square of the distance between them. As a result, the electric field between widely spaced capacitor plates is less than when they are closely spaced.

26. True — The degree to which molecules align themselves with the electric field (the dielectric constant) determines the capacitance of a capacitor.

27. (d) Air. — The dielectric constant of air is approximately 1. Other dielectric constants are greater than one.

28. 90 pF. — $C = \dfrac{0.225\ kA}{d} = \dfrac{0.225 \times 1 \times 4}{.01} = \dfrac{.900}{.01} = 90$ pF.

29. Excessive voltage will distort the dielectric molecules until electrons are torn from the atoms. These electrons will then flow through the dielectric from one plate to another, destroying the dielectric.

30. The working voltage is the maximum voltage that can be steadily applied to a capacitor without causing a breakdown.

PRACTICE EXERCISE SOLUTIONS (Continued)

31. **The dielectric strength and the thickness of the dielectric material are two main factors. A safety factor is also included by most manufacturers.**

32. **A varying length of time, which depends on the dielectric characteristics. A good capacitor that has very low leakage may hold a charge for several months. As the capacitor ages, its ability to hold a charge for a length of time usually decreases.**

33. **False — The changing current will divide between C_1 and C_2 so that the voltages across both capacitors are the same.**

34. **50 μF. — The total capacitance in a parallel circuit is the sum of the individual capacitance values. Therefore:**

$$\begin{aligned} C_T &= C_1 + C_2 + C_3 \\ &= 5 + 15 + 30 \\ &= 50\ \mu F. \end{aligned}$$

35. $C_T = C_1 + C_2 + C_3 + C_4 + C_5$.

36. $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$

37. $C_T = \frac{C_1 C_2}{C_1 + C_2}$

38. **False — Since the capacitors are in series, the same current must flow through each capacitor.**

39. **True — The value of the source voltage will be divided between the capacitors.**

40. **6 μF. —** $\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$

$$= \frac{1}{10} + \frac{1}{20} + \frac{1}{60}$$

$$= \frac{6}{60} + \frac{3}{60} + \frac{1}{60} = \frac{10}{60}$$

$$\text{Since } \frac{1}{C_T} = \frac{10}{60},\ C_T = \frac{60}{10} = 6\ \mu F.$$

PRACTICE EXERCISE SOLUTIONS (Continued)

41. $E_{C_1} = 90$ volts; $E_{C_2} = 60$ volts. — First, the total capacitance must be determined:

$$C_T = \frac{C_1C_2}{C_1 + C_2} = \frac{20 \times 30}{20 + 30} = \frac{600}{50} = 12\ \mu F.$$

The total charge is then:

$$Q = C_TE = 1.5 \times 10^2 \times 12 \times 10^{-6} = 18 \times 10^{-4} \text{ coulombs.}$$

Then the voltage drop across each capacitor is:

$$E_{C_1} = Q/C_1 = 18 \times 10^{-4}/20 \times 10^{-6} = .9 \times 10^2 = 90 \text{ volts.}$$

$$E_{C_2} = Q/C_2 = 18 \times 10^{-4}/30 \times 10^{-6} = .6 \times 10^2 = 60 \text{ volts.}$$

42. 40 μF. — The capacitance of the series combination is:

$$C_{series} = \frac{C_2C_3}{C_2 + C_3} = \frac{25 \times 100}{25 + 100} = \frac{2500}{125} = 20\ \mu F.$$

The total capacitance is:

$$C_T = C_1 + C_{series}$$

$$= 20 + 20 = 40\ \mu F.$$

43. fixed

44. Because two flat plates would have to be relatively large. It saves more space to roll or fold the plates and dielectric into a compact unit.

45. (d) waxed paper.

46. (a) a film of metal. — The metal film is deposited onto a suitable dielectric. A capacitor of this type is smaller, for the same capacitance value, than a paper foil type. It also has a higher operating voltage rating and is "self-healing."

47. False — This description fits a regular mica capacitor. A silver mica capacitor uses a film of silver deposited on mica sheets.

PRACTICE EXERCISE SOLUTIONS (Continued)

48. (a) high dielectric constant. — This permits construction of capacitors with high capacitance and a small physical size.

49. (b) high stability. — These capacitors are more commonly considered for applications where long-term operation might affect the capacitance of less stable types.

50. False — The oxide film is formed on the capacitor's positive electrode (anode) by the forming voltage applied during manufacture.

51. The can should be mounted on a fiber insulating plate, which is then fastened to the chassis. This insulates the capacitor from the chassis.

52. (b) are polarized. — Proper polarity must be observed when making connections to an electrolytic capacitor or it will be damaged. This type of capacitor is not used on extremely high voltages or for ac applications.

53. To reform the oxide film dielectric by electrochemical action. This film tends to disappear if the capacitor is not operated for a long period.

54. more or greater — Tantalum capacitors also have very great stability compared to other electrolytic capacitors.

55. Change the effective plate area, the spacing between the plates or the dielectric.

56. The stator plates are insulated from the frame and shaft. The rotor plates make electrical connection to the shaft and the frame.

57. (a) 10 pF. — This represents the capacity between stator and rotor plates when they are completely unmeshed.

58. If a capacitor has a positive temperature coefficient, its capacitance varies in the same direction as the temperature changes of the capacitor. (A positive change in temperature causes an increase in capacitance.) A negative temperature coefficient is just the reverse of this.

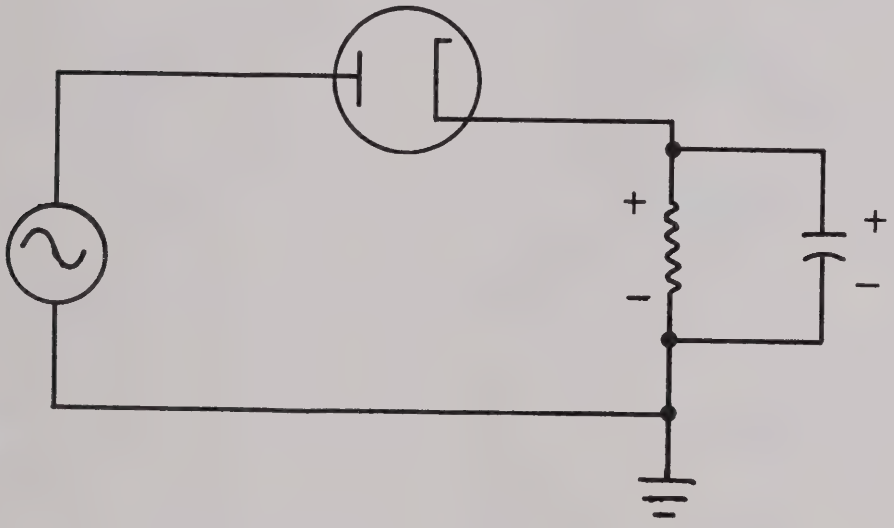
59. 250.03 pF. — $\Delta C = \frac{\text{T.C.} \times C \times t}{1{,}000{,}000} = \frac{40 \times 250 \times 3}{1{,}000{,}000} = .03$ pF.

60. 4700 pF; 10%. — The yellow and violet A and B dots indicate 47. The red D dot indicates a multiplier of 100 for a value of 4700 pF. The silver E dot indicates a 10% tolerance. The white first dot indicates an EIA unit. The meaning of the black N dot must be determined from the manufacturer's specs.

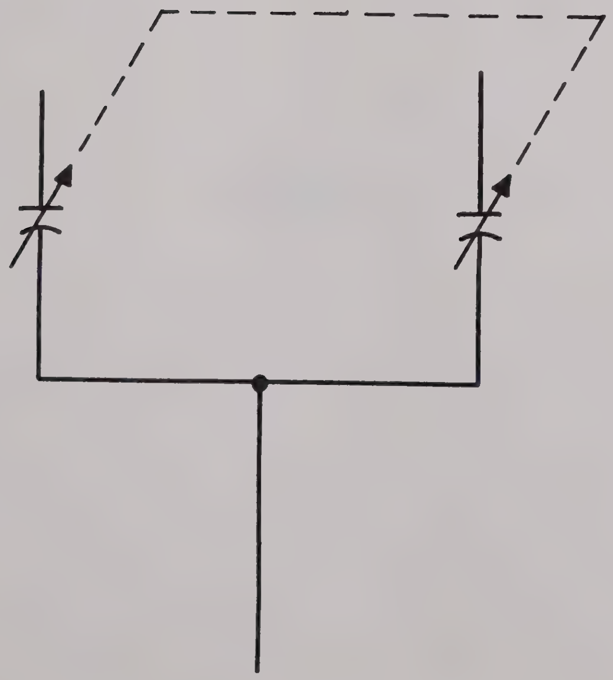
PRACTICE EXERCISE SOLUTIONS (Continued)

61. The white first dot indicates the EIA unit.

62. Since an electrolytic capacitor is used, polarity must be observed. The curved plate is labeled negative while the straight plate is positive.



63.



DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

1037A
EXAMINATION CHECK SHEET

1037A

1. A - A SIMPLE CAPACITOR CAN CONSIST OF -- TWO METAL SURFACES SEPARATED BY A DIELECTRIC. Additional plates may be added along with additional layers of dielectric to increase the value of capacitance.

2. B - WHILE A CAPACITOR IS DISCHARGING -- THE VOLTAGE ACROSS IT IS DECREASING. When a capacitor charges, the voltage across it increases until it equals the source voltage. When discharging the voltage decreases from the source voltage to zero.

3. A - THE BASIC UNIT OF CAPACITANCE IS THE -- FARAD. A farad is the amount of capacity which accepts a charge of one coulomb (6.28×10^{18} electrons) when the applied voltage is one volt.

4. C - IF A .1 μF CAPACITOR HAS ACCUMULATED A CHARGE OF $.25 \times 10^{-4}$ COULOMBS, WHAT IS THE VOLTAGE ACROSS THE CAPACITOR? -- 250 VOLTS. To determine the voltage, use the formula $E = Q/C$.

$$E = .25 \times 10^{-4}/.1 \times 10^{-6} = 2.5 \times 10^{2} \text{ or } 250 \text{ volts.}$$

5. C - IN A PARALLEL CIRCUIT, IF $C_1 = 10\ \mu F$ AND $C_2 = 2\ \mu F$, THE TOTAL CAPACITANCE WOULD BE -- 12 μF. The total capacitance in a parallel circuit is the sum of the individual capacitances. Thus,

$$C_T = C_1 + C_2 = 10\ \mu F + 2\ \mu F = 12\ \mu F.$$

6. B - SUPPOSE THAT TWO CAPACITORS, $C_1 = 10\ \mu F$ AND $C_2 = 40\ \mu F$, ARE CONNECTED IN SERIES ACROSS A 150 VOLT SOURCE. WHAT IS THE VOLTAGE DROP ACROSS THE 10 μF CAPACITOR? -- 120 VOLTS. First determine the total capacity:

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{10 \times 40}{10 + 40} = \frac{400}{50} = 8\ \mu F.$$

The total charge is then:

$$Q = CE = 8 \times 10^{-6} \times 1.5 \times 10^{2} = 12 \times 10^{-4} \text{ coulombs.}$$

Since the capacitors are in series, they accumulate the same amount of charge and the voltage across each capacitor is:

$$E_{C_1} = Q/C_1 = 12 \times 10^{-4}/10 \times 10^{-6} = 1.2 \times 10^{2} = 120 \text{ volts}$$

$$E_{C_2} = Q/C_2 = 12 \times 10^{-4}/40 \times 10^{-6} = .3 \times 10^{2} = 30 \text{ volts.}$$

7. C - IN A SERIES CIRCUIT CONSISTING OF TWO CAPACITORS $C_1 = 20\ \mu F$ AND $C_2 = 30\ \mu F$, THE TOTAL CAPACITANCE WOULD BE -- 12 μF. The total capacitance of two capacitors in series is:

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2} = \frac{20 \times 30}{20 + 30} = \frac{600}{50} = 12\ \mu F.$$

8. D - DOUBLING THE AREA OF THE CAPACITOR PLATES WILL CAUSE THE CAPACITANCE TO -- DOUBLE. According to the basic formula for the capacitance of a simple two plate capacitor $C_{(pF)} = \frac{0.225\ kA}{d}$, the capacitance is directly proportional to the area of the plates.

9. C - IF A SHORT CIRCUIT OCCURS WHEN A BREAKDOWN VOLTAGE IS APPLIED TO A CAPACITOR, BUT THE CAPACITOR RETURNS TO NORMAL OPERATING CONDITIONS WHEN THE VOLTAGE OVERLOAD IS REMOVED, THE CAPACITOR IS SAID TO BE -- SELF-HEALING. This type of capacitor is generally of the metal film type, in which the damaged spot vaporizes.

10. B - THE TYPE OF CAPACITOR WHICH MAY BE DAMAGED IF THE APPLIED VOLTAGE REVERSES POLARITY IS THE -- ELECTROLYTIC CAPACITOR. Due to the construction of an electrolytic capacitor, its polarity cannot be reversed.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1037A

Example: Bicycles have

A ☐ B ■ C ☐ D ☐

A. one wheel. B. two wheels. C. three wheels. D. four wheels.

1. A ☐ B ☐ C ☐ D ☐ **A simple capacitor can consist of** (A) two metal surfaces separated by a dielectric. (B) a dielectric and one metal surface. (C) one metal surface. (D) two dielectrics separated by a metal surface.

2. A ☐ B ☒ C ☐ D ☐ **While a capacitor is discharging,** (A) the amount of charge stored on the plates increases. (B) the voltage across it is decreasing. (C) the voltage across it is increasing. (D) electrons are building up on the negative plate.

3. A ☒ B ☐ C ☐ D ☐ **The basic unit of capacitance is the** (A) farad. (B) micro. (C) ohm. (D) ampere.

4. A ☐ B ☐ C ☒ D ☐ **If a .1 μF capacitor has accumulated a charge of .25 × 10^{-4} coulombs, what is the voltage across the capacitor?** (A) 25 volts. (B) .25 volt. (C) 250 volts. (D) 2500 volts.

5. A ☐ B ☐ C ☒ D ☐ **In a parallel circuit, if $C_1 = 10\ \mu$F and $C_2 = 2\ \mu$F, the total capacitance would be** (A) 2 μF. (B) 8 μF. (C) 12 μF. (D) 10 μF.

6. A ☐ B ☒ C ☐ D ☐ **Suppose that two capacitors, $C_1 = 10\ \mu$F and $C_2 = 40\ \mu$F, are connected in series across a 150-volt source. What is the voltage drop across the 10 μF capacitor?** (A) 30 volts. (B) 120 volts. (C) 60 volts. (D) 100 volts.

7. A ☐ B ☐ C ☒ D ☐ **In a series circuit consisting of two capacitors, $C_1 = 20\ \mu$F and $C_2 = 30\ \mu$F, the total capacitance would be** (A) 25 μF. (B) 20 μF. (C) 12 μF. (D) 30 μF.

8. A ☐ B ☐ C ☐ D ☒ **Doubling the area of the capacitor plates will cause the capacitance to** (A) remain the same. (B) decrease to one-half. (C) increase four times. (D) double.

9. A ☐ B ☐ C ☒ D ☐ **If a short circuit occurs when a breakdown voltage is applied to a capacitor, but the capacitor returns to normal operating conditions when the voltage overload is removed, the capacitor is said to be** (A) in need of replacement. (B) off tolerance. (C) self-healing. (D) variable.

10. A ☐ B ☒ C ☐ D ☐ **The type of capacitor which may be damaged if the applied voltage reverses polarity is the** (A) ceramic capacitor. (B) electrolytic capacitor. (C) mica capacitor. (D) paper capacitor.

EXPERIMENT 5

CAPACITORS

PARTS NEEDED

1 - Design Console
1 - Multimeter and Test Leads
- Modular Connectors
1 - 4.7 kΩ, 1/2 W, Resistor
2 - Test Prod Spring Adapters
1 - Diode
1 - 10 μF Capacitor
1 - 1000 μF Capacitor
- Hookup Wire

OBJECTIVE

The purpose of this experiment is to show the charging and discharging action of a capacitor.

PART 1

PROCEDURE

1. Set up the circuit shown in Figure 5-1. Diode D_1 and capacitor C_1 are used only to apply a dc voltage to R_1 and C_2. The charging action of C_2 is to be investigated. When setting up the circuit, be sure to observe the polarity of C_1 and C_2.

2. Connect the multimeter across C_2. The voltage across the capacitor will be about 20 volts, so use a range which will handle that amount of voltage. The capacitor may initially have a slight charge. This would be indicated by a small voltage across it.

3. Turn the on/off switch of the design console to the on position and observe the reaction of the multimeter. You should see the needle move quickly at first, and then it slows down until the final voltage is reached. The time necessary to reach full voltage will be about 25 seconds, so allow enough time for the capacitor to fully charge. Record the final voltage reading below.

________________ volts

4. Place the on/off switch of the design console to the off position. With a piece of hookup wire, connect the two leads of C_2 together. Note: You will obtain an arc when the capacitor is discharged in this manner.

5. Place the multimeter across R_1, and turn the on/off switch of the design console to the on position. Again observe the reaction of the meter. The needle should jump to a high voltage reading and then reduce to about zero. The time necessary will again be about 25 seconds.

6. Turn the on/off switch of the design console to the off position, and remove R_1 from the circuit. This isolates C_2 from the rest of the circuit.

7. With C_2 isolated, measure the voltage across the capacitor. You will notice that the voltage is maintained across the capacitor for a long period of time. From this observation we can conclude that the capacitor can store energy.

8. Reinsert R_1 and recharge the capacitor by turning the design console on/off switch to the on position. Determine when C_2 is fully charged by measuring the voltage across it. When a full charge has been reached, turn off the design console. Remove R_1 again and, while measuring the voltage across C_2, connect R_1 in parallel with C_2 to form the circuit shown in Figure 5-2. You will notice the voltage decreases rapidly at first, then it reduces slower after the voltage has dropped to about half the full value.

CONCLUSION

In this experiment we see that when a dc voltage is applied to a resistor capacitor (RC) circuit, the capacitor will charge to the voltage applied. When a resistance is connected across the charged capacitor, the capacitor will discharge similarly to the way in which it has charged. The capacitor is capable of storing a charge for some length of time. The higher the capacitance value, the longer the charge will last. For this reason, high value capacitors should be discharged before working on a circuit.

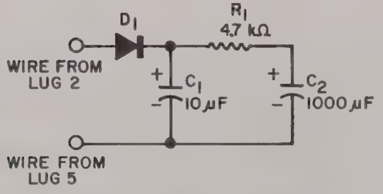


FIGURE 5-1

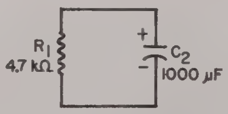


FIGURE 5-2

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

9502-5A&B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

9502-5B

1. A - WHEN A CAPACITOR CHARGES, THE RATE OF CHARGE IS FASTER AT THE START AND SLOWS AS THE CAPACITOR REACHES FULL CHARGE. -- TRUE.
As the capacitor reaches a full charge, the rate of charge slows. This action can be observed with the meter as in Step 3 of this experiment.

2. D - WHEN THE CAPACITOR IS FULLY CHARGED, WHAT IS THE VOLTAGE ACROSS R_1 IN FIGURE 5-1? -- ZERO.
With the capacitor fully charged, there will be no current in the circuit, thus no voltage across the resistor.

3. B - IN THE CIRCUIT OF FIGURE 5-1, WHAT IS THE VOLTAGE ACROSS CAPACITOR C_2 THE INSTANT THE DC VOLTAGE IS APPLIED ACROSS THE COMBINATION OF R_1 AND C_2? -- ZERO.
The capacitor acts as a short during the first instant of time; therefore, the voltage across the capacitor is zero.

4. A - IN THE CIRCUIT OF FIGURE 5-1, WHAT IS THE VOLTAGE ACROSS RESISTOR R_1 THE INSTANT A VOLTAGE IS APPLIED ACROSS THE COMBINATION OF R_1 AND C_2? -- FULL APPLIED VOLTAGE.
The instant the dc voltage is applied to the circuit of Figure 5-1, capacitor C_2 will appear to be a short circuit. Therefore, the voltage across R_1 will be the full applied voltage.

5. C - IN FIGURE 5-2, WHAT IS THE VOLTAGE ACROSS THE RESISTOR AT ANY POINT IN TIME? -- EQUAL TO THE VOLTAGE ACROSS THE CAPACITOR.
The capacitor acts as a source and the resistance voltage will be equal to the capacitor voltage.

9502-5A

All explanations are the same as for 9502-5B except for those given below.

3. B - WHAT IS THE VOLTAGE ACROSS THE CAPACITOR THE INSTANT THE VOLTAGE IS APPLIED? -- ZERO.
The capacitor acts as a short during the first instant of time; therefore, the voltage across the capacitor is zero.

4. A - WHAT IS THE VOLTAGE ACROSS THE RESISTOR THE INSTANT THE VOLTAGE IS APPLIED? -- FULL APPLIED VOLTAGE.
The instant that voltage is applied to the circuit of Figure 5-1, capacitor C_1 will appear to be a short circuit. Therefore, the voltage across R_1 will be the full applied voltage.

ELECTRONIC POWER SUPPLIES

1040

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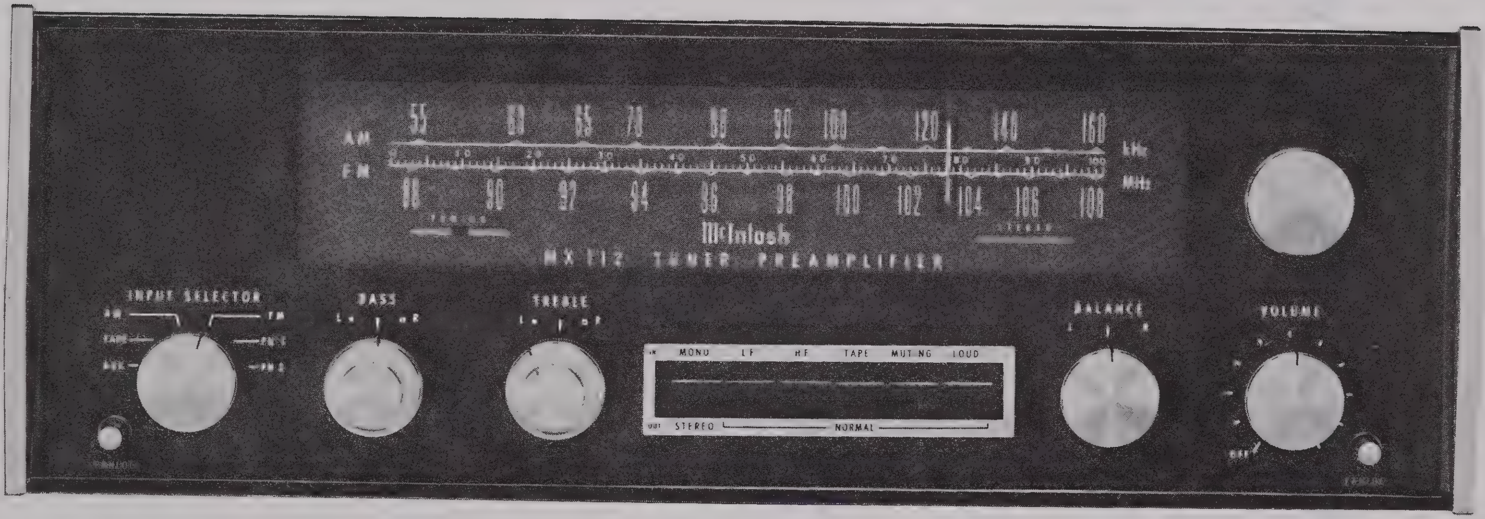

This AM/FM Stereo Tuner Preamplifier employs two separate full-wave power supplies to supply the various dc operating voltages. The operating voltages range from 9.5 volts to 75 volts.
Courtesy McIntosh Laboratory Inc.

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Many people are "marking time" in their chosen trade or profession because they haven't had the preparation to take them farther. Somebody better qualified is always ahead of them. If they but knew it, they could soon become superior in their work through home study.

—Webster H. Pearce

ELECTRONIC POWER SUPPLIES

Most electronic circuits require dc operating voltages. The term **"POWER SUPPLY"** is given to the circuit or section of the equipment that supplies the dc operating voltages. In portable equipment, the power supply generally consists of a "battery." The **BATTERY** is an energy-conversion device that converts chemical energy into electrical energy.

Electronic equipment used in industry and the home usually operates from the ac power line. In these cases, the power supply is a circuit which converts the ac line voltage into the required dc operating voltages.

CELLS AND BATTERIES

Over the years the terms "cell" and "battery" have been confused and often used to indicate the same unit. A single device which develops electric energy is called a **CELL**. On the other hand, a group of cells connected together is called a BATTERY.

There are two basic types of cells. One is the **PRIMARY CELL**. In the primary cell, once the materials are consumed by the chemical action, the cell is no longer usable. The other type of cell, the **SECONDARY CELL**, can be recharged and used over and over again.

Primary Cells

The PRIMARY CELL, as mentioned above, cannot be recharged. Once the chemicals are used up, the cell is no longer usable. The most common primary cell is the type used in flashlights, transistor radios and similar devices. Figure 1 shows the basic construction of this type of cell. Generation of electric energy occurs because the molecules of the chemicals in the electrolyte break down into positive and negative ions. The positive ions take electrons from the carbon-manganese mix and make the carbon rod positive. The negative ions make the zinc can negative. The emf developed by the cell causes electron flow in the external circuit, as shown in Figure 1. The emf is developed by the cell as long as the chemical action continues.

The cell pictured in Figure 1 is called a "dry cell" since the electrolyte is in the form of a paste. The emf developed by this type of cell is approximately 1.5 to 1.6 volts when new. As the chemicals are used up, the developed emf gradually reduces to zero.

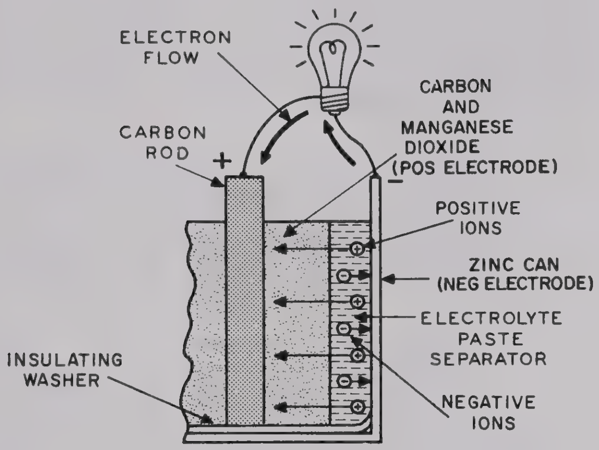


Figure 1

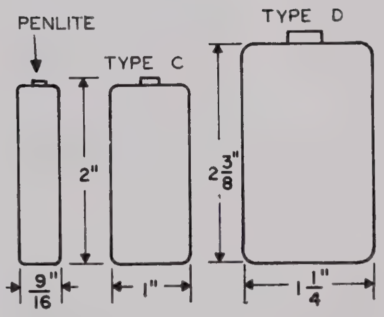


Figure 2

The emf developed by a cell is not dependent upon the size of the cell, but on the materials which go into its construction. The physical size determines how much current it can supply. Thus, no matter how large the cell of Figure 1 is made, its developed emf will be 1.5 to 1.6 volts. Figure 2 shows some common sizes of dry cells. The small penlite cell (AA cell) is designed for low-current applications such as in pocket transistor radios. It can supply currents up to 25 mA. The C size can supply currents up to 80 mA while the larger D size can supply currents up to 150 mA. These are typical current ratings suggested by a manufacturer. The cells can supply more current than this but their life will be greatly reduced.

The dry cell shown in Figure 1 employs zinc and carbon as the major materials and is often called a ZINC-CARBON CELL. By employing different materials, a greater current capacity, as well as a more constant output voltage, can be obtained. The MERCURY CELL is more efficient, can operate longer and supply a more constant output voltage than the zinc-carbon cell. Due to the different materials used in the mercury cell, its developed emf is about 1.345 volts.

Another type of cell that is widely used today is the ALKALINE CELL. This cell develops an emf of about 1.4 to 1.5 volts. It has a longer life than the zinc-carbon cell and can also supply more current for a given cell size. The developed emf, however, decreases gradually as the cell is used.

Figure 3 shows the characteristics of the three types of cells. Note that the output voltage of the conventional zinc-carbon cell drops off quite rapidly compared to that of the alkaline cell. The mercury cell, however, provides a nearly constant output voltage for its life. The mercury cell is therefore suitable for applications which require a constant supply voltage such as in electronic instruments. The alkaline and zinc-carbon cells are suitable for applications not requiring constant supplies, such as transistor radios, photographic flash units, flashlights, etc.

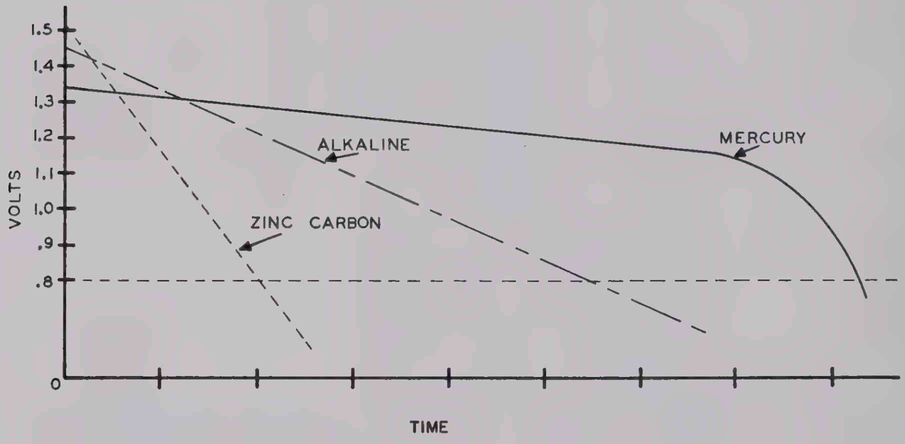


Figure 3

There are a large number of so called "dry cell BATTERY CHARGERS" available today. As far as the zinc-carbon, mercury and most alkaline cells are concerned, they cannot be recharged. In general, all these units do is heat the cell by passing a current through it. This tends to improve the internal chemical action, extending its life. In any event, once the chemicals are used up, the cell is no longer usable. Some alkaline cells can be partially recharged and used over again. However, these are more expensive than the conventional cells.

Secondary Cells

The SECONDARY CELL differs from the primary cell in that it can be recharged and used over and over again. The most common examples are the LEAD-ACID cell battery used in automobiles and the NICKEL-CADMIUM cells used in most cordless appliances.

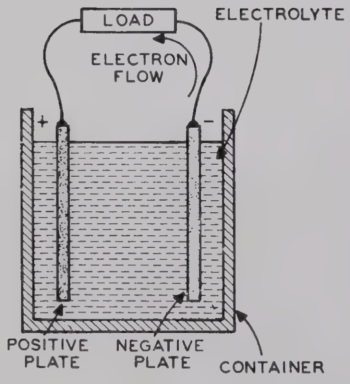


Figure 4

Figure 4 shows the basic construction of the lead-acid cell. The positive and negative plates are made out of lead and the electrolyte is a sulphuric acid solution. The emf is developed by ion flow to the two plates, as in the cell of Figure 1. The emf developed by the lead-acid cell is about 2.1 volts and decreases gradually until the acid in the electrolyte is absorbed by the plates. Since the lead-acid cell uses a liquid electrolyte, it is often called a WET CELL. To restore the action in the lead-acid cell, it can be CHARGED by passing a current through it in the opposite direction, as shown in Figure 5. This returns the acid to the electrolyte and the cell can be used again.

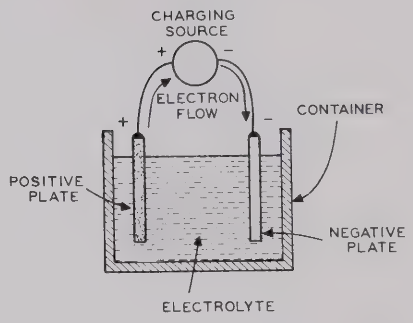


Figure 5

The nickel-cadmium cell operates much like the lead-acid cell. However, it employs different materials and develops an emf of about 1.2 volts. As the cell is used or "discharged," the voltage decreases as in the lead-acid cell. The nickel-cadmium cell is charged in the same manner as the lead-acid cell by passing a current through it in the opposite direction.

The nickel-cadmium cell has several advantages over the lead-acid wet cell. It is more rugged and can supply more current for a given cell size. The nickel-cadmium cell can also be made with the electrolyte in paste form and built in a container like a conventional dry cell. These are the types commonly used in cordless appliances and other pieces of electronic equipment. Some lead-acid cells are also put into a dry cell form.

There are many other types of secondary cells. They are not as common as the nickel-cadmium cell (nicad) or lead-acid cell, and they are made for special applications. One type is the SILVER CELL, which is widely used in aerospace applications. It can supply a large amount of current from a small size cell and it is very rugged.

The FUEL CELL is a new type of device. In this unit, materials are consumed to develop an emf. For example, on many of the manned space flights, fuel cells are used to generate the electric energy for the spacecraft by combining oxygen and hydrogen. The by-product of this process is water which can be used for the astronauts' water supply.

The SOLAR CELL is a special type of device which converts light energy into electrical energy. These devices are employed on satellites and space probes to supply electric energy for the electronic equipment and charge the batteries for use during periods of darkness.

Secondary Cell Ratings

The capacity of a cell is defined as the amount of current that the cell can supply for a specific period of time. The most common method of rating lead-acid cells is referred to as the **AMPERE-HOUR** (A.H.). Basically, the ampere-hour rating is equal to the discharge current multiplied by the number of hours required to discharge the cell to a certain output voltage. More recent methods of rating the performance of lead-acid cells are known as the cranking performance and reserve capacity methods.

The CRANKING PERFORMANCE, or COLD CRANKING POWER rating method, is specified as the number of amperes that a battery can deliver, maintaining at least 1.2 volts per cell, for 30 seconds at 0°F. The RESERVE CAPACITY rating method is specified as the number of minutes required to discharge a new, fully charged battery at 80°F, when using a 25-ampere load and maintaining at least 1.75 volts per cell.

To illustrate the ampere-hour rating, assume that a cell can supply 5 amperes for 20 hours before the cell output voltage drops to an unusable level. The ampere-hour rating of this cell is 5 × 20, or 100 ampere-hours. An important point to note is that the same cell may not be able to supply 100 amperes for one hour. The ampere-hour capacity usually decreases as the discharge time decreases. For example, the cell just described may only be able to supply 25 amperes for 2 hours. At this discharge rate, the same cell has a capacity of 50 ampere-hours. It is therefore important that the discharge time be known in addition to the ampere-hour rating. The ampere-hour rating, along with the discharge time, gives a full picture of the cell capacity.

BATTERIES

Many applications require voltages or load currents higher than those provided by a single cell. In these cases, individual cells can be interconnected to provide the desired voltage or current.

Cells In Series

To obtain a voltage higher than that of one cell, a SERIES CONNECTION must be used. The total voltage is equal to the sum of the individual cell voltages. Figure 6 shows three 1.5-volt dry cells connected in series. THE POSITIVE TERMINAL OF ONE CELL IS CONNECTED TO THE NEGATIVE TERMINAL OF THE NEXT CELL. This must be observed if the total voltage is to be the sum of the cell voltages. The total voltage developed by the three cells is 1.5 + 1.5 + 1.5, or 4.5 volts. If four 1.5-volt cells were connected in series, the total voltage would be 1.5 + 1.5 + 1.5 + 1.5, or 6 volts. Thus, by connecting cells in series, a much higher voltage can be obtained. The available current, however, is equal to that of a single cell.

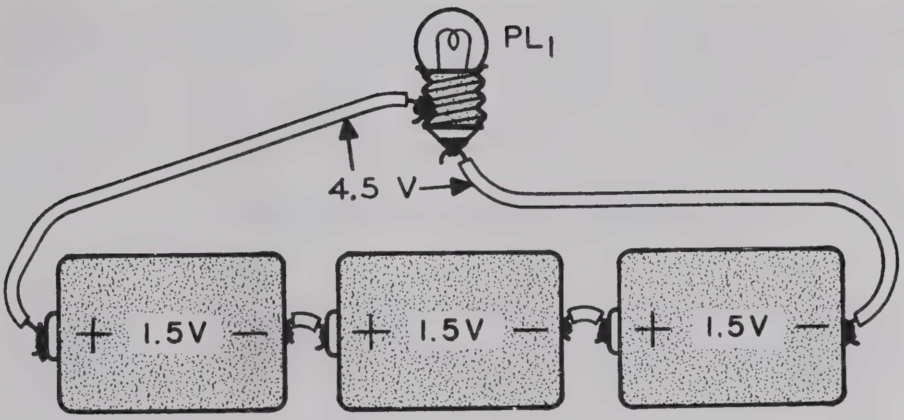


Figure 6

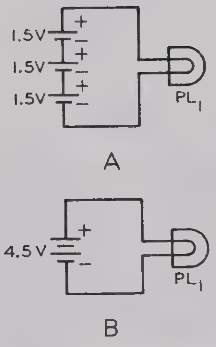


Figure 7

Figure 7A shows a schematic diagram of the circuit of Figure 6. The symbol for each cell consists of a long and a short bar. The long bar represents the positive terminal and the short bar represents the negative terminal.

The 12-volt automotive battery shown consists of six lead-acid cells connected in series. Each cell provides 2.1 volts fully charged for a total of 12.6 volts. The case is made of polypropylene.
Courtesy Battery Division, Globe-Union, Inc.

A separate symbol is used for each cell in Figure 7A. It is common practice to use another symbol if two or more cells are connected together to form a battery. Figure 7B shows the battery symbol which consists of two long bars and two short bars. The number of bars in the battery symbol does NOT indicate the number of cells in the battery. The total output voltage of the battery is usually indicated alongside the symbol, as shown in Figure 7B.

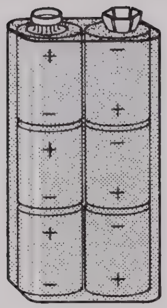


Figure 8

Figure 8 shows the construction of a 9-volt battery of the type commonly used in portable transistor radios. This battery consists of six 1.5-volt cells connected in series. The six 1.5-volt cells provide a potential of 9 volts.

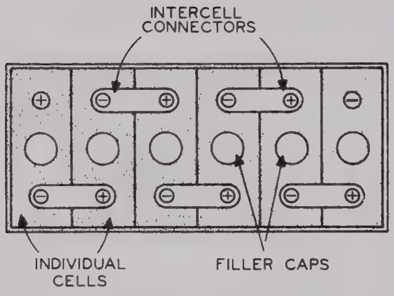


Figure 9

The top view of an automobile battery is shown in Figure 9. This 12-volt automobile battery consists of six lead-acid cells connected in series. The positive terminal of one cell is connected to the negative terminal of the next cell. Lead straps are used to interconnect the cells.

Cells In Parallel

Frequently, the current that one cell can supply is not adequate for a particular application. In these cases, a PARALLEL CONNECTION of cells can be used. The total available current is the sum of the currents that each cell can supply. For example, if two similar cells are connected in parallel, the total available current is twice that of one cell.

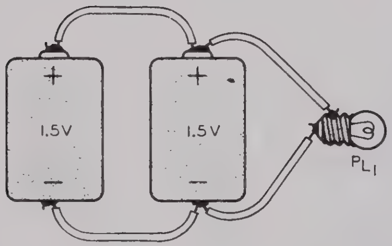


Figure 10

Figure 10 shows two cells connected in parallel. A schematic diagram of this circuit appears in Figure 11. NOTE THAT THE POSITIVE TERMINAL OF ONE CELL IS CONNECTED TO THE POSITIVE TERMINAL OF THE NEXT CELL. THE SAME HOLDS FOR THE NEGATIVE TERMINALS. The voltage supplied to the lamp is the same as the voltage of one cell. Thus, connecting cells in parallel does not increase the voltage but it does increase the available current. The battery symbol shown in Figure 7B is also used for parallel-connected cells. When cells are connected in parallel, they should all have the same output potential.

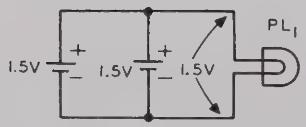


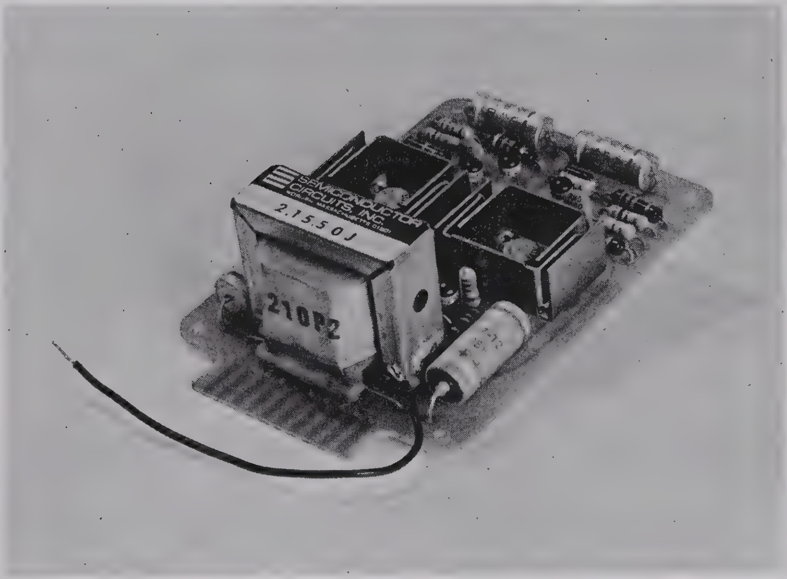
Figure 11

To illustrate the advantage of connecting cells in parallel, assume that two 40 ampere-hour (A.H.) nickel-cadmium cells are connected in parallel. The two parallel-connected cells have a total capacity of 80 A.H., or twice the capacity of one cell.

The series and parallel connection of cells can be summarized as follows. When cells are connected in series to form a battery, the total voltage is the sum of the individual cell voltages and the available current is equal to that of one cell. When cells are connected in parallel to form a battery, the total available current is the sum of the currents available from each individual cell, and the total voltage is equal to the voltage of one cell.

AC OPERATED POWER SUPPLIES

As mentioned earlier, many pieces of equipment operate from the ac power line. The ac line voltage is generally not usable directly since most electronic equipment requires dc operating voltages. In addition, the required dc operating voltages may be higher or lower than the line voltage. To meet these requirements, a number of components are used to make up the power supply circuit. First, a transformer can be used to step up or step down the ac line voltage to the required value. Then, one or more diodes are used to convert the ac voltage to a pulsating dc voltage. Finally, capacitors and inductors or resistors are used to smooth out the pulsating dc voltage.



The above photo shows an ac operated power supply mounted on a plug-in printed circuit board.

Courtesy Semiconductor Circuits Inc.

Figure 12 shows the basic block diagram of an ac operated power supply. The transformer supplies an ac voltage to the rectifier circuit which is higher or lower than the ac line voltage. The rectifier circuit converts the ac voltage into a pulsating dc voltage. This pulsating dc voltage is then applied to a filter which smooths out the variations, providing a constant dc output voltage.

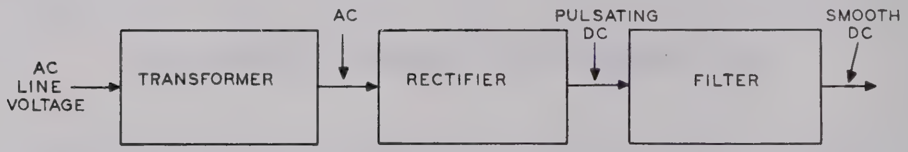


Figure 12

Half-Wave Rectifier

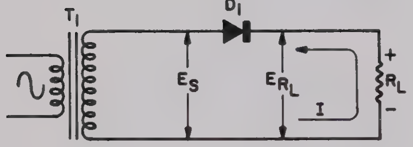


Figure 13

There are two basic types of rectifier circuits. One is called the **HALF-WAVE RECTIFIER**. Figure 13 shows the basic half-wave rectifier circuit. T_1 supplies the desired ac voltage, E_S, to the diode. Diode D_1 is connected in series with the T_1 secondary and the load, represented by R_L. It is common practice to represent the various circuits connected to a power supply with a resistor labeled R_L.

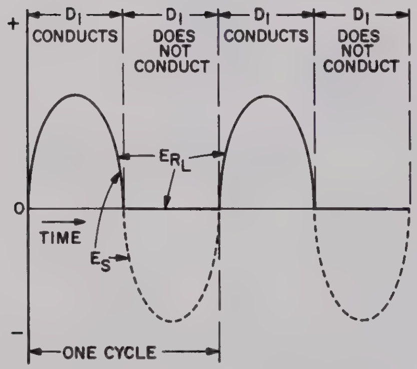


Figure 14

A diode conducts when its anode is positive with respect to the cathode. Thus, in Figure 13, when the top of the T_1 secondary is positive with respect to the bottom, D_1 conducts, and there is current through the load in the direction shown by the arrow. On the opposite alternation, when the top of the T_1 secondary is negative with respect to the bottom, D_1 is nonconductive and there is no current through R_L.

Figure 14 shows the waveform of the voltage appearing across R_L. Note that D_1 conducts on each positive alternation. Thus, the current through R_L consists of pulses, one each positive half-cycle, in the same direction. In some applications this "pulsating dc" may be satisfactory. However, in most applications a smoother dc current is required. This is obtained by passing the pulsating dc output of the rectifier through a filter circuit.

Full-Wave Rectifier

The disadvantage of the half-wave rectifier circuit is that only one current pulse is developed in the load during each cycle of the ac supply. This makes the filtering of the pulsating dc more difficult than in the **FULL-WAVE**

The following Practice Exercise questions cover the subjects which you have just studied. They are:

CELLS AND BATTERIES

PRIMARY CELLS

SECONDARY CELLS

SECONDARY CELL RATINGS

BATTERIES

CELLS IN SERIES

CELLS IN PARALLEL

1. What is a primary cell?

2. How is the emf developed in the cell of Figure 1?

3. The ______________ cell provides an almost constant emf during its life.

4. What are the approximate emf's developed by the mercury and alkaline cells?

5. Compared to the zinc-carbon cell, the alkaline cell can supply energy for a ____________ period of time.

6. All alkaline cells can be recharged. True or False?

7. What are the emf's developed by a lead-acid cell and by a nickel-cadmium cell?

8. How is a lead-acid cell charged?

9. If a cell can supply 3 amperes for 15 hours, what is its A.H. capacity?

10. When cells are connected in series, the total voltage is (a) the difference between the individual cell voltages, (b) the sum of the individual cell voltages, (c) equal to the voltage of one cell.

11. If nine 1.2-volt cells are connected in series, what is the total voltage?

12. Suppose that you need a potential of about 6 volts. How many lead-acid cells would you need and how would you interconnect them?

13. Draw the symbol for a single cell and indicate the positive and negative terminals.

14. Draw the symbol for a battery and indicate the positive and negative terminals.

15. When cells are connected in parallel, (a) the total voltage is the sum of the individual cell voltages, (b) the total available current is the sum of the current each cell can supply.

16. What is the output voltage developed by three lead-acid cells connected in parallel?

RECTIFIER. In the full-wave rectifier, two current pulses are developed in the load during each cycle of the ac supply.

Figure 15 shows the schematic diagram of a full-wave power supply. This circuit requires a center-tapped ac supply, and therefore, generally employs a transformer. The half-wave supply, however, can operate directly from an ac supply if the voltage is the desired value.

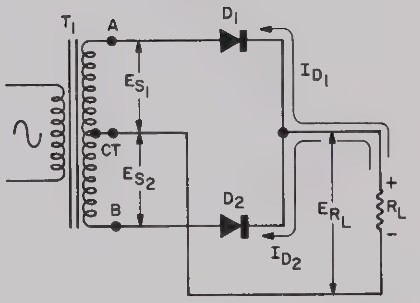


Figure 15

To examine the circuit operation of a full-wave rectifier, consider the alternation when the top of the T_1 secondary (point A) is positive with respect to the bottom (point B). Under these conditions, the top of the T_1 secondary is positive with respect to the center tap (CT), and the bottom of the T_1 secondary is negative with respect to the center tap. As a result, the anode of D_1 is positive with respect to its cathode and D_1 conducts current through R_L in the direction shown by the I_{D_1} arrow. At the same time, the anode of D_2 is negative with respect to its cathode and D_2 is nonconductive.

On the next alternation, the voltage across the T_1 secondary reverses polarity. Now the top of the T_1 secondary is negative with respect to the center tap and the bottom is positive with respect to the center tap. Under these conditions, D_2 is forward biased and D_1 is reverse biased. D_2 conducts current through R_L, as shown by the I_{D_2} arrow, and D_1 is nonconductive.

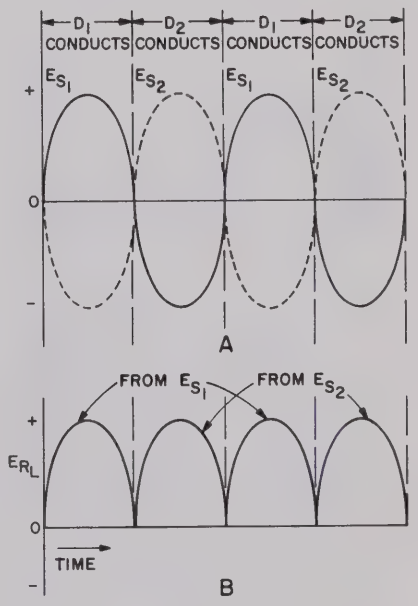


Figure 16

Thus, in the full-wave rectifier circuit, the diodes conduct on opposite alternations and there are two pulses of current through the load during each cycle of the ac supply. Figure 16A shows the two input voltage waveforms, E_{S_1} and E_{S_2}, to the rectifiers. E_{S_1} (solid waveform) goes positive when E_{S_2} (dashed waveform) goes negative during one half-cycle, and opposite conditions occur during the next half-cycle. Figure 16B shows the waveform of the voltage, E_{R_L}, that appears across the load resistor, R_L, in the full-wave rectifier. Compare this to the waveshape of the half-wave rectifier in Figure 14. Although still pulsating dc, the output of the full-wave circuit is easier to filter since two current pulses occur during each cycle.

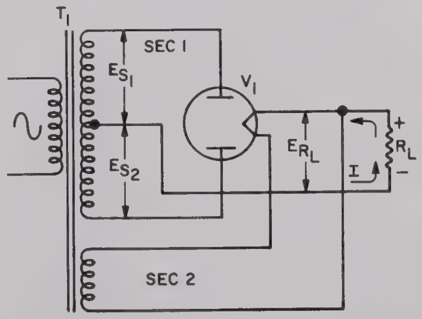


Figure 17

Semiconductor diodes have all but replaced vacuum tube diodes in rectifier circuits. Of course, vacuum tubes are still used in older equipment, as well as in special applications such as high-voltage rectifiers, etc. Figure 17 shows a full-wave rectifier employing a duodiode (two diodes in one envelope). V_1 is directly heated so the cathode connection is made to the filament. Filament voltage for V_1 is supplied by SEC 2 on T_1. The operation of the circuit is identical to that of Figure 15. When the top of the T_1 secondary in Figure 17 is positive with respect to the center tap, electrons flow from the cathode of V_1 to the top plate. On the opposite alternation electrons flow from the cathode to the lower plate of V_1. In power supplies for tube circuits, the transformer will usually have one or more additional secondary windings that supply other required filament voltages.

The major drawback of a vacuum tube rectifier is the filament power that it requires, along with the resultant heat. In some circuits, the rectifier filament may consume more power than does the remainder of the circuit in the equipment.

Bridge Rectifier

Figure 18A shows another type of full-wave rectifier called the **BRIDGE RECTIFIER**. Notice that the circuit employs a power transformer which does not have a center-tapped secondary. Instead, the circuit uses four diodes to obtain full-wave rectification.

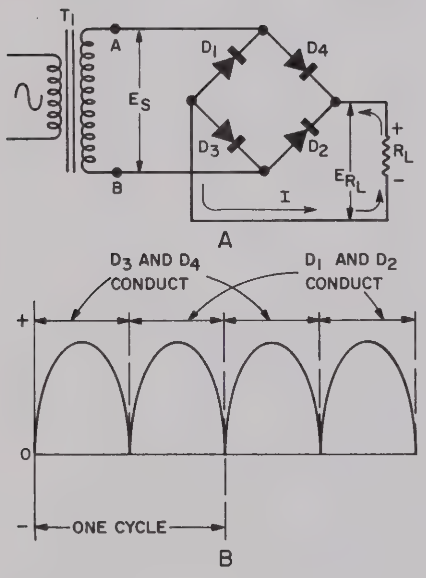


Figure 18

To examine circuit operation, assume that the top of the secondary, point A, is positive with respect to the bottom, point B. With point A positive, the cathode of D_1 and the anode of D_4 are positive. At the same time, with point B negative, the cathode of D_3 and the anode of D_2 are negative. As a result, D_4 and D_3 are conductive, while D_1 and D_2 are nonconductive. With D_3 and D_4 conductive, electrons flow from point B through D_3 up through R_L and then through D_4 to point A.

On the other alternation of the ac source, point A is negative with respect to point B. Thus, the cathode of D_1 and the anode of D_4 are negative. At the same time, the cathode of D_3 and the anode of D_2 are positive. As a result, D_1 and D_2 are conductive, while D_3 and D_4 are nonconductive. With D_1 and D_2 conductive, electrons flow from point A through D_1, up through R_L and then through D_2 to point B. Note that the current through R_L is in the same direction when either set of diodes conducts. Since D_1 and D_2 conduct on one alternation and D_3 and D_4 conduct on the other, two current pulses are produced for each cycle of the ac supply to provide full-wave rectification. The bridge output waveform is shown in Figure 18B.

Since a bridge rectifier does not require a tapped transformer, it rectifies the full secondary voltage on each alternation. Thus, the pulsating dc output is about equal to the peak voltage across the entire secondary. Compared to a conventional full-wave rectifier, a bridge rectifier provides pulsating dc of about twice the amplitude using a secondary with the same number of turns. The PIV for the diodes is equal to the peak value of the supply voltage since the two diodes are in series.

Any of the filter circuits shown earlier can be used with the bridge rectifier of Figure 18A. Although semiconductor diodes are shown in Figure 18A, vacuum tube diodes can also be used. However, in most cases semiconductor diodes are used because they are smaller and do not require a filament supply.

FILTER SYSTEMS

As mentioned earlier, the pulsating dc output of the rectifier circuit is not smooth enough for most circuits. A **FILTER** is used to smooth out the pulsating dc.

Filter Capacitors

The simplest filter is a capacitor connected across the output of the half-wave rectifier shown in Figure 19A. As the first rectifier current pulse rises, electrons flow into the lower plate of C_1 in the direction of the charge arrow and out of the upper plate, through D_1 and the secondary of T_1. This action charges the capacitor to the peak of the secondary voltage, E_S. At the same time, electrons also flow through R_L, in the direction of the load current arrow.

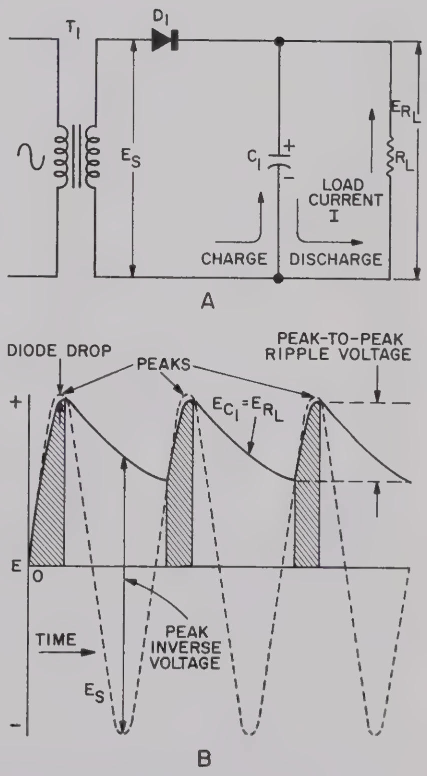


Figure 19

As E_S decreases, the capacitor discharges. Because D_1 permits the flow of electrons only in one direction, the capacitor cannot discharge through D_1 and the transformer secondary. Therefore, the discharge current flows from the lower plate of C_1 through R_L to the upper capacitor plate.

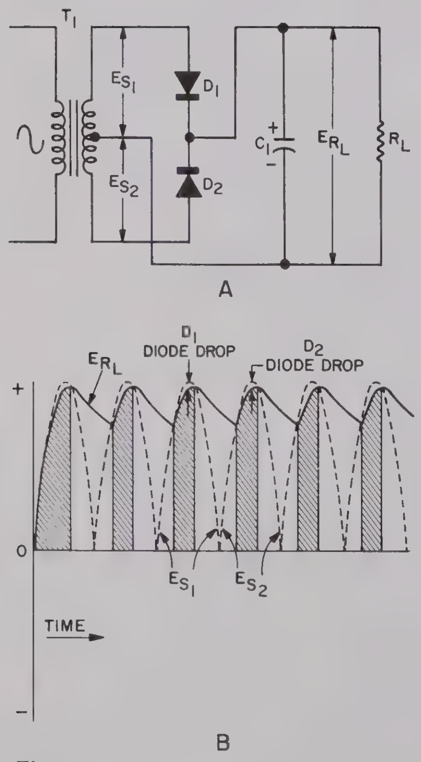
The value of C_1 is chosen so that it does not discharge as rapidly as the secondary voltage decreases. Therefore, the load current and capacitor voltage do not decrease as rapidly as the secondary voltage. Once the secondary voltage becomes less than the voltage across C_1, D_1 is reverse biased and becomes nonconductive. D_1 conducts only long enough to charge C_1. Capacitor C_1 is discharged only partially by the time the next pulse recharges it to the peak of the secondary voltage.

As a result of this action, the load voltage pulses are no longer like those in Figure 14. In Figure 19B, the dashed line curve represents the secondary voltage, E_S. The solid line curve represents the variations of the voltage across C_1 and R_L. This varying voltage across the filter capacitor is called the **RIPPLE VOLTAGE**, and is a component of the output voltage.

The alternations of secondary voltage E_S, which make the diode anode positive, charge C_1 until the peak value is reached. The time during which D_1 conducts and C_1 charges is indicated by the shaded area under the curve. Thereafter, C_1 discharges through R_L, as indicated by the unshaded areas, until the next rising positive pulse exceeds the voltage remaining on capacitor C_1; then D_1 conducts and C_1 charges again. Since R_L represents the load, the load current has the same waveform as the solid line voltage curve of Figure 19B.

By choosing a large enough value for the capacitor, C_1 discharges only a small amount between pulses from the rectifier, and the ripple voltage amplitude is low.

Let's examine the conditions in Figure 19A during the alternation when D_1 is cut off. During this time, the top of the T_1 secondary is negative with respect to the bottom. As a result, the secondary voltage is series aiding with the C_1 voltage, and the total of these voltages appears across D_1. The peak value of this reverse voltage occurs during the peak of the negative alternation of the secondary voltage, and it is called the **PEAK INVERSE VOLTAGE (PIV)**. D_1 must be able to withstand this voltage without breaking down.



A

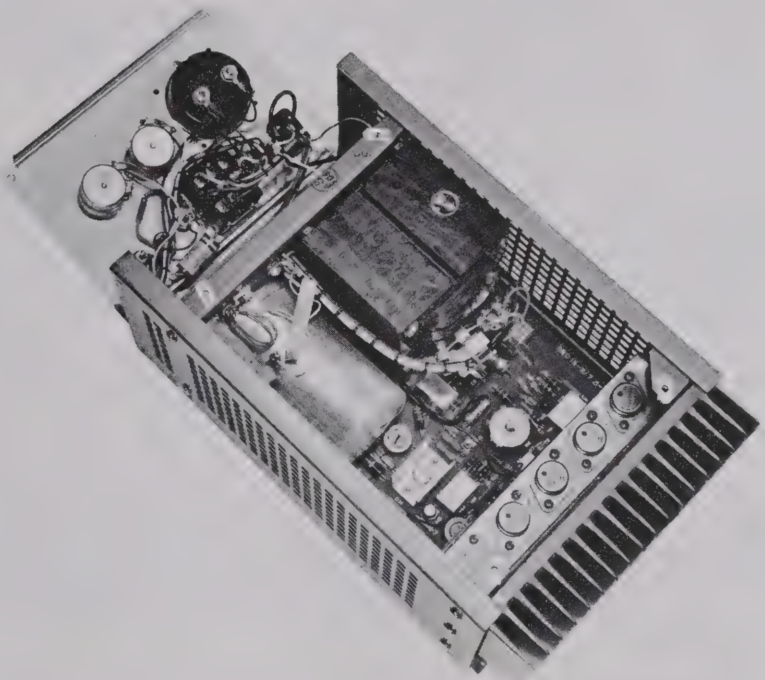
B

Figure 20

Since C_1 charges to the peak of the secondary voltage when D_1 conducts, the peak inverse voltage is twice the peak value of the secondary voltage. As an example, suppose the T_1 secondary voltage is 100 volts. Its peak value is 1.414×100, or approximately 141 volts. The peak inverse voltage is 2×141, or 282 volts. D_1 in Figure 19A must therefore have a PIV rating of at least 282 volts. For a full-wave rectifier using a center-tapped power transformer, the PIV is the peak value of the entire secondary voltage. For a half-wave rectifier, the PIV is twice the peak value of the secondary voltage.

The filtering action is similar when a capacitor is placed across the load terminals of a full-wave rectifier circuit, as shown in Figure 20A. Again, capacitor C_1 charges during part of the rising portion of each positive pulse, and then discharges through R_L until the next pulse arrives. In this case, the lower plate of capacitor C_1 connects to the center tap of the T_1 secondary. For each cycle of the applied voltage, the upper end of the secondary is positive during one alternation and the lower end is positive during the other alternation, with respect to the center tap. Therefore, two positive pulses charge C_1 during each cycle.

In Figure 20B, the dashed line curve represents the series of charging voltage pulses applied across C_1 and R_L, and the shaded areas represent the time during which C_1 is charging. As in Figure 19B, the solid line curve shows that C_1 charges to the peak voltage of each pulse, and then discharges through R_L, until the next pulse arrives to recharge it. This curve thus represents the voltage across C_1 and R_L, and the current in R_L. Note that the solid charging line lags behind the dashed supply line. This lag results because it takes time to charge the capacitor.



The filter capacitor in this power supply is the can mounted next to the power transformer. Note the large physical size of the capacitor. High values of capacitance are required in solid state circuits where the load requirements are high currents at low voltage.

Courtesy Raytheon Co.
Sorensen Operation

For the same supply voltage frequency, in Figure 20 the charging pulses occur twice as often as those in Figure 19. Therefore, C_1 in Figure 20 has a shorter interval for discharge. Consequently, the variations of the ripple voltage across C_1 in the full-wave circuit are less than they are when using the same filter in the half-wave circuit.

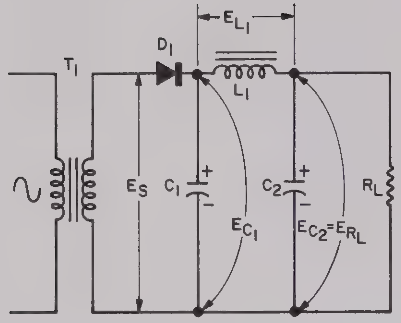


Figure 21

Filter Inductor or Resistor

In most applications, the filter action of a single capacitor does not produce a sufficient reduction of the ripple voltage. To improve the filter action, a filter **CHOKE** and another capacitor can be added, as shown in Figure 21. CHOKE L_1 is an inductor consisting of a winding on an iron core, and its filter action is due to the self-induction which opposes any change in current. Connected in series with the rectifier and load, the choke carries the entire load current.

As the applied voltage, E_S, causes the current to rise, the self-induced voltage in the choke opposes the change, and thus prevents the current from rising immediately to its peak. The filter input capacitor, C_1, charges to the peak of the applied voltage during the first current pulse in the same manner as C_1 does in Figure 19. Then, as E_S decreases, C_1 discharges through R_L and L_1. At the same time, this decreasing load current induces a voltage in the choke in a direction which tends to maintain the current.

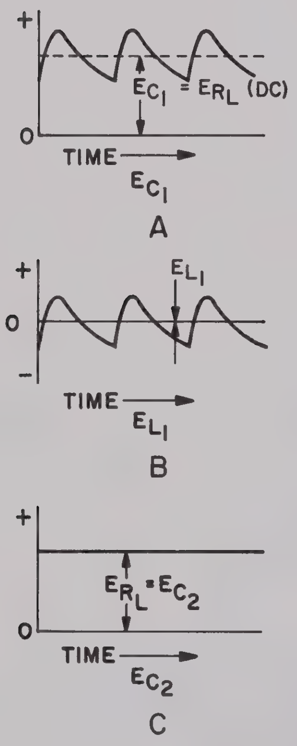


Figure 22

The waveforms across the capacitors and inductor are shown in Figure 22. The E_{C_1} voltage waveform across the filter input capacitor, C_1, is the same as the E_{R_L} (or E_{C_1}) waveform of Figure 19B. C_1 performs the same function in the circuits of both Figure 19A and Figure 21. This waveform is shown in Figure 22A.

The E_{L_1} voltage across choke L_1 is shown in Figure 22B. Because the choke resistance is very low, almost no dc voltage is dropped across L_1. The counter emf of L_1 opposes only the ac ripple changes.

The output voltage (E_{C_2} or E_{R_L}), taken across C_2 and R_L, is shown in Figure 22C. A very small amount of ripple is still present, but, as shown in the figure, it is too small to see, and in most instances, too small to be of any consequence.

L_1 and C_2 are connected in series across C_1; therefore, the sum of their voltages, $E_{L_1} + E_{C_2}$, is equal to E_{C_1}. The voltage E_{C_2} forms the output voltage of the filter, and is applied across the terminals of the load R_L.

In Figure 21, the voltage E_{C_1} is composed of two components: direct voltage, and the ripple, which varies up and down at the supply frequency. The inductor has a counter emf which opposes only the ac or ripple. Therefore, most of the ac ripple voltage appears across L_1 and very little ~~across~~ C_2.

On the other hand, L_1 offers minimum counter emf to the direct voltage, and very little dc voltage appears across L_1, leaving almost all of it across C_2.

In applications where the load requires a small current, the choke of Figure 21 is often replaced by a filter resistor, shown as R_1 in Figure 23. R_1 is connected in series between the rectifier and load R_L, and forms the series arm of the filter, $C_1R_1C_2$.

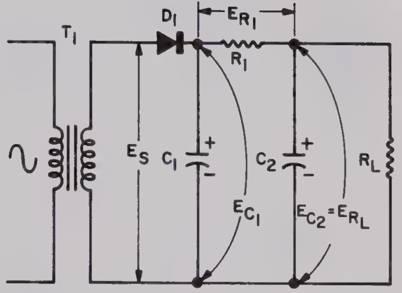


Figure 23

In Figure 23, the voltage E_{C_1} is applied to R_1 and C_2 in series. Resistor R_1 does not discriminate between frequency components, but since C_2 passes ac frequencies and blocks the direct voltage component, a part of the direct voltage and most of the alternating voltage appear across R_1, while the output voltage, E_{C_2}, is almost entirely direct voltage.

Since the direct voltage drop, E_{R_1}, across resistor R_1 is lost as far as the load is concerned, it is desirable that this voltage be kept low compared with the direct voltage, E_{C_2}, across the filter output. According to Ohm's Law: for a given current, E_{R_1} is directly proportional to the resistance of R_1. The relatively low cost, size and weight of a filter resistor make it advantageous in those applications which do not require a large current from the power supply. When a large current is needed, a filter choke is used.

The low-pass filter of Figures 21 and 23 are called **PI-TYPE FILTERS**. The name pi comes from the fact that the filter, as it is usually drawn in a schematic diagram, looks like the greek letter π (called pi). The term "low-pass" refers to the fact that the filter reduces the amplitude of alternating voltages, and that the higher the frequency, the greater the reduction, because the capacitors have less time to discharge between alternations. In effect, the filter "passes" low frequencies (or dc) and blocks high frequencies.

As shown by the solid line curve of Figure 19B, once the input capacitor C_1 has been charged by the first rectifier current pulse, it never becomes completely discharged while the power supply is in operation. The voltage E_{C_1}, in Figures 21 and 22, has polarity opposite that required to produce current in the circuit made up of C_1, D_1 and the transformer secondary winding. After the first pulse, current can exist in this circuit only when E_S has sufficient amplitude and proper polarity to overcome the capacitor voltage, E_{C_1}. In Figures 19B and 20B, the narrow shaded areas indicate that this period is short and exists between the point on the rising voltage slope when E_S is equal to E_{C_1} and the peak of the applied voltage. For this reason, the transformer and rectifier provide energy in short pulses to the input filter capacitor.

Usually, the load requires a constant supply of energy from the power supply. Therefore, the filter is a device which receives energy in short pulses of rectified current and stores the electric energy in the capacitors from which current is taken steadily by the load as needed.

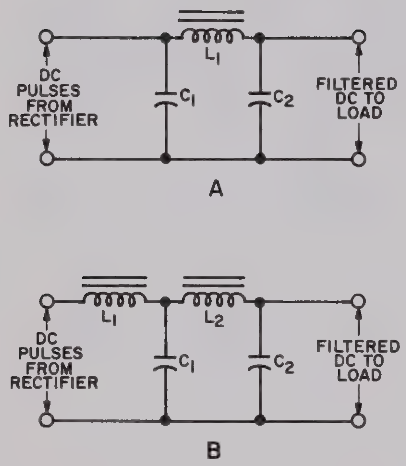


Figure 24

Types of Filters

In addition to being classified as low-pass, the filters employed in power supplies are also designated according to the type of component employed at the input or rectifier end. In the pi-type filter of Figure 24A, capacitor C_1 forms the input component, and therefore, this arrangement is called a **CAPACITOR INPUT** filter. This type of filter is used in the circuits of Figures 21 and 22. The filter of Figure 24B is composed of two "L-sections," L_1C_1 and L_2C_2, and since L_1 forms the input component, this arrangement is called a **CHOKE INPUT** filter.

The most common power supply filter arrangements are shown in Figures 24A and 24B. Figure 24A is a single-section, pi-type filter; Figure 24B consists of two L-section filters.

The choke input filter provides better regulation, and generally is employed in applications which require good regulation. On the other hand, the capacitor input arrangement provides a somewhat higher output voltage with a given power transformer and rectifier. It is used for equipment which does not have such high regulation requirements. Where the higher output voltage of a capacitor input filter is needed along with high regulation, the filter output is usually followed by a regulator circuit.

REGULATION

In many applications, it is necessary that the power supply output voltage remain nearly constant, regardless of load current variations during the normal operation of the equipment. This important power supply characteristic is referred to as **REGULATION**.

In Figure 21, an increase in load current decreases the charge stored in the output capacitor, C_2, and therefore decreases the available output voltage, E_{C_2}. An increase in current in the choke is required to recharge C_2. The increased current increases the voltage drop across the choke which reduces the direct voltage available at the output terminals of the filter. The increased current also reduces the charge on C_1 and, therefore, the rectifier current pulses must increase in amplitude to recharge C_1. The increased current is

The following Practice Exercise questions cover the subjects which you have just studied. They are:

AC OPERATED POWER SUPPLIES

HALF-WAVE RECTIFIER

FULL-WAVE RECTIFIER

BRIDGE RECTIFIER

FILTER SYSTEMS

FILTER CAPACITORS

FILTER INDUCTOR OR RESISTOR

17. Name the three basic sections of an ac operated power supply and describe the function of each.

18. The output of the half-wave rectifier circuit of Figure 13 is smooth dc. True or False?

19. In the half-wave rectifier circuit, how many pulses of current pass through the load during each cycle of the ac supply?

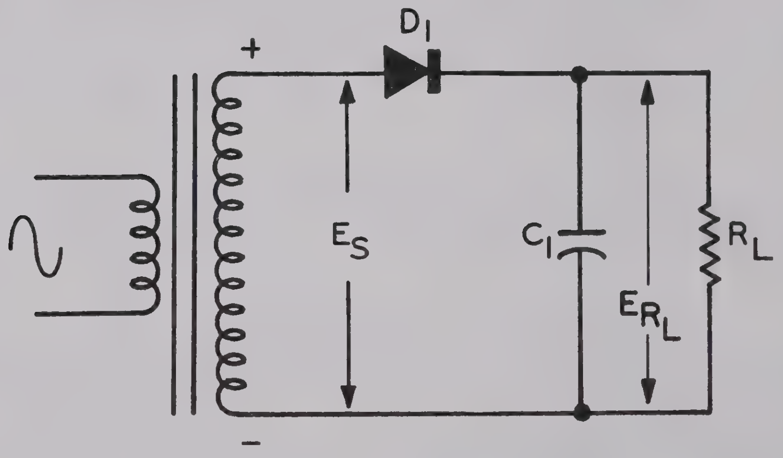
20. How does a full-wave rectifier differ from a half-wave rectifier?

21. What would be the effect if D_1 and D_2 were reversed in the circuit of Figure 15?

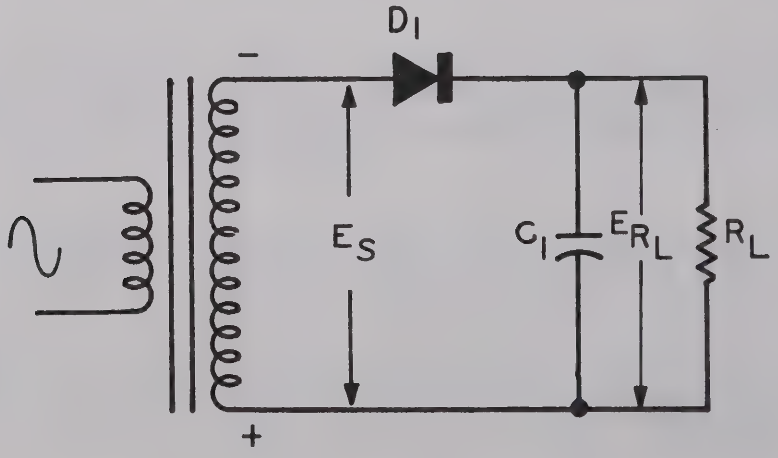
22. A bridge rectifier is a half-wave rectifier. True or False?

23. In the circuit of Figure 18A, which diodes conduct when the top of the secondary is positive with respect to the bottom?

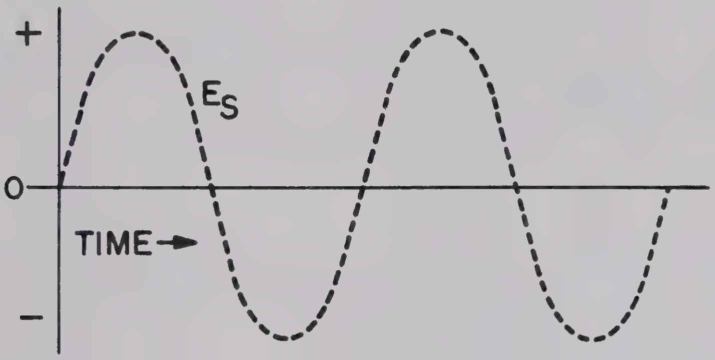
24. In the circuit below, use arrows to indicate the path or paths of current when the polarity of the transformer is as shown. Use + and — signs to indicate the polarity of the voltage across C_1 and R_L.



25. In the circuit below, use arrows to indicate the path or paths of rectified current when the polarity of the transformer is as shown. Assume C_1 is charged from the previous alternation. Show the polarity of the voltage across R_L.



26. The dashed sinewave below shows the secondary voltage, E_S, for the circuits of Practice Exercises 24 and 25. Draw a solid line waveform to show the rectified voltage across C_1 and R_L.



27. The waveform drawn for Practice Exercise 26 is dc because it never changes polarity. However, it is not pure dc since it has an ac component. The ac component is called ______________________.

28. What would happen to the amplitude of the ripple voltage if the load current were decreased (load resistance increased)?

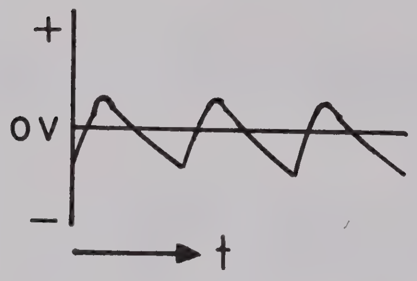
29. When selecting a rectifier diode, you must make sure it can handle the expected load current. What other rating is important?

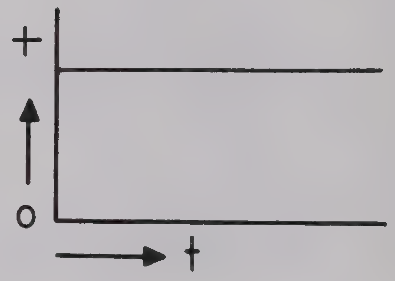
30. It is easier to filter the output voltage of a power supply with a high load current than one with a low load current. True or False?

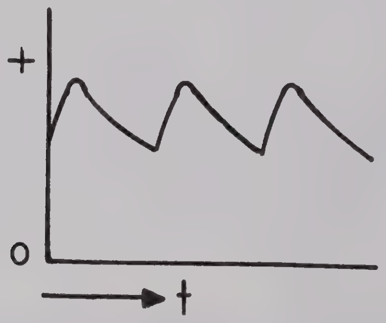
31. The ripple frequency of a full-wave power supply is twice that of a half-wave power supply. True or False?

32. It is easier to filter the output voltage of a full-wave power supply than a half-wave power supply. True or False?

33. Shown below are the waveforms that will be found across C_1, C_2 and L_1 in Figure 21. Properly label the waveforms as E_{C_1}, E_{C_2} and E_{L_1}.







34. What is the advantage of the filter choke, L_1, of Figure 21 over the filter resistor, R_1, of Figure 23?

35. The output of a power supply operated from a 400-Hz power line is easier to filter than one operated from a 60-Hz power line. True or False?

36. One or the other diode conducts at all times in a filtered full-wave power supply. True or False?

carried by rectifier D_1 and the secondary winding of the transformer. Since both D_1 and T_1 have some resistance, the increased voltage drop across them reduces the portion of E_S which is available for charging C_1.

To reduce these undesirable effects, the filter capacitors should have high capacitance; the choke should provide high inductance; and the transformer secondary, the rectifier and the choke should have low resistance. Semiconductor diodes have a lower internal resistance than vacuum tube diodes and therefore provide somewhat better regulation.

In practice, each power supply is designed to provide a certain maximum output, known as the full-load current. The voltage at the output terminals is highest under no-load conditions, and reduces to some definite value at the rated full-load current. The less the output voltage changes with load current variation, the better the regulation is. Because most circuits work best at some particular voltage, GOOD REGULATION is a desirable power supply characteristic.

The regulation of a power supply is expressed as a percentage and can be found with a simple formula:

$$\%\ \text{Regulation} = \frac{E_N - E_F}{E_F} \times 100 \qquad (1)$$

where: E_N is the no-load output voltage, and

E_F is the full-load output voltage.

As an example for use of this formula, assume that a power supply has a no-load output voltage of 300 volts and a full-load output voltage of 250 volts. The percentage of regulation is:

$$\%\ \text{Regulation} = \frac{300 - 250}{250} \times 100$$

$$\%\ \text{Regulation} = \frac{50}{250} \times 100$$

$$= .2 \times 100 = 20\%.$$

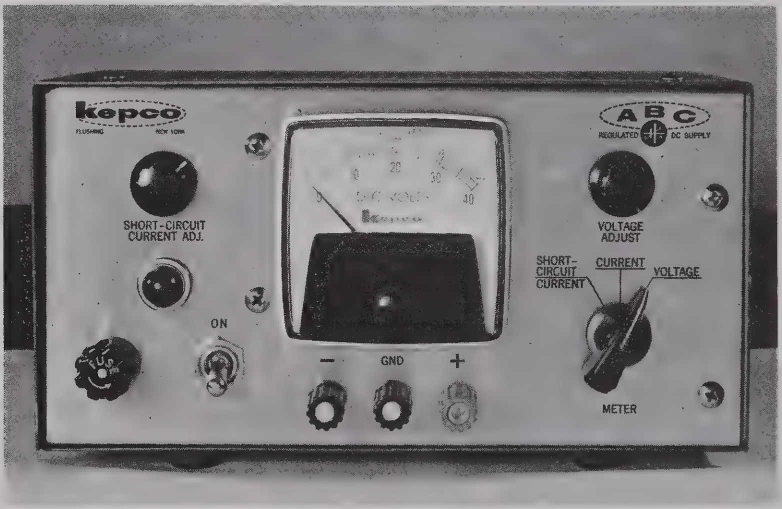
As another example, suppose the no-load output voltage of a power supply is 50 volts and the full-load output voltage is 48 volts. The percentage of regulation is:

$$\% \text{ Regulation} = \frac{50 - 48}{48} \times 100$$

$$\% \text{ Regulation} = \frac{2}{48} \times 100$$

$$= .0417 \times 100 = 4.17\%.$$

The less the output voltage changes under load, the lower the percentage of regulation. A low percentage of regulation indicates a good power supply, and a high percentage of regulation indicates a poor power supply. The lower the internal resistance of the power supply, the better the regulation.



This power supply has an adjustable output voltage along with a circuit which protects against excessive load current. These features are valuable when testing circuits where shorts could cause excessive damage.
Courtesy Kepco Inc.

BLEEDER RESISTOR

To show the complete current path, the load was represented by resistor R_L in the previous figures. However, the load is not a part of the power supply

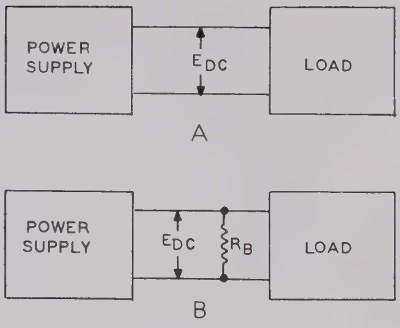


Figure 25

proper. In Figure 25A, the transformer, rectifiers and filter are represented by the block labeled power supply. The output voltage, E_{DC}, is applied to the load, which represents the combination of circuits and components which receive their dc operating voltages and currents from the power supply.

Under usual operating conditions, the total resistance of the load varies from time to time, forcing the power supply to deliver more or less current. As mentioned before, the output voltage, E_{DC}, varies with changes in load current, and the smaller these variations are, the better the regulation is.

To improve the regulation, it is common practice to employ a **BLEEDER RESISTOR** across the output terminals of the filter, as shown by resistor R_B in Figure 25B. Therefore, the supply must furnish a total current which is equal to the sum of the load current plus that carried by the BLEEDER RESISTOR. The bleeder maintains a constant current drain on the supply so that load current changes constitute a smaller percentage of change than they would if there weren't any bleeder resistor.

With the load connected across the bleeder, its current is only a portion of the total output, and any variations in the load current result in smaller changes in the total supply current. Thus, the changes in E_{DC} with load current variations are reduced, and use of the bleeder resistor improves the regulation. Also, when the load is disconnected, the bleeder provides a discharge path for the power supply filter capacitors.

TRANSFORMERLESS POWER SUPPLIES

Because of cost, weight or space limitations, some electronic equipment contains power supplies that do not use power transformers. In this type of equipment, the rectifier input is connected directly to the power line through an off-on switch.

AC/DC Power Supplies

Many of the small table model vacuum tube or transistor radio receivers are called ac/dc radios. This name was given to the receivers since their power supplies can be operated from either an ac or dc power line. Although dc power lines are not in common use today, the name ac/dc is still used to describe a particular type of power supply. Figure 26 shows a typical ac/dc power supply for a vacuum tube radio. D_1 is a semiconductor diode which rectifies the ac line voltage, providing half-wave rectification. C_1, C_2 and R_2 form a pi-type filter. Since this supply operates directly from the ac line, its maximum output voltage is limited to the peak value of the ac line voltage.

In actual practice, the output voltage for this type of circuit is usually around 150 volts. Rectifier D_1 is protected by current-limiting resistor R_1.

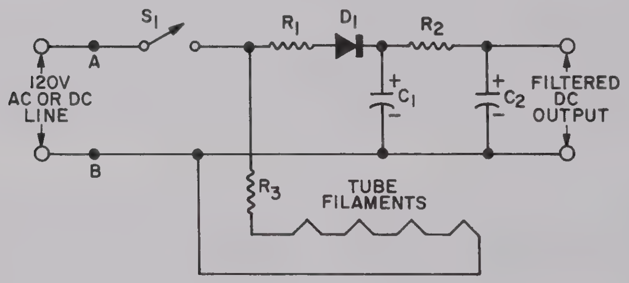


Figure 26

Since a power transformer is not used in the ac/dc supply, the tube filaments must also be operated from the ac line. This is usually done by connecting the tube filaments in series. Such an arrangement is referred to as a **SERIES STRING** heater circuit. In this circuit, the vacuum tube heaters and R_3 form a series circuit. The value of R_3 is determined by the values of the filament resistances so that the proper voltages appear across the tube filaments.

As mentioned earlier, the power supply of Figure 26 was originally designed to operate from both ac and dc power lines. To operate this supply from a dc line, input lead A is connected to the positive side of the line and input B is connected to the negative side of the line. When operated on dc, D_1 conducts continuously, acting like a closed switch.

The ac/dc supply of Figure 26 offers the advantages of simplicity and low cost. This is largely because no power transformer is used. AC/DC supplies are normally used in low-priced radio receivers, TV receivers and phonographs. Radios using transistors or integrated circuits, instead of vacuum tubes, do not have filament circuits. Clock radios using transistors or integrated circuits cannot operate from dc lines because of their ac clock motors. Portable record players that may be battery operated use dc motors, and could therefore operate directly from dc lines.

Notice in Figure 26 that one side of the ac line is connected to the common point in the circuit, which is usually the chassis. Figures 27 and 28 show the effects of this arrangement. Figure 27 shows one side of the ac line connected directly to the chassis of a radio receiver. This side of the ac line is also grounded to a water pipe. (One side of the ac line is grounded to

The following Practice Exercise questions cover the subjects which you have just studied. They are:

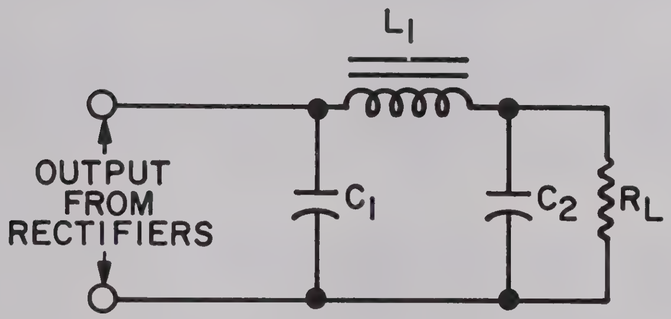
FILTER SYSTEMS

TYPES OF FILTERS

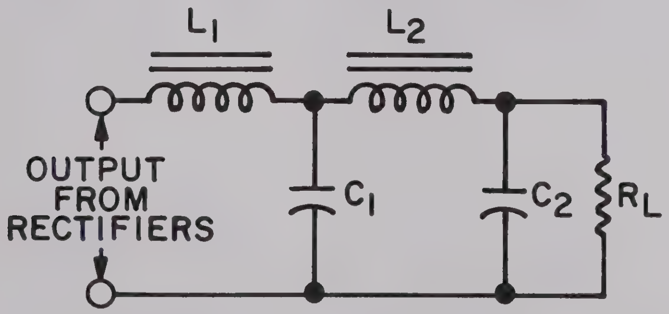
REGULATION

BLEEDER RESISTOR

37. What type of filter is represented by the diagram shown below?



38. What type of filter is represented by the diagram shown below?



39. What is the advantage of a capacitor input filter?

40. What is the advantage of a choke input filter?

41. The ability of a power supply to maintain a constant output voltage regardless of load current variations depends on its (a) filtering, (b) regulation, (c) ripple voltage, (d) no-load voltage.

42. An increase of load current normally causes the output voltage of a power supply to (a) increase, (b) decrease, (c) remain the same.

43. How can the regulation of a power supply be improved?

44. If the no-load output voltage of a power supply is 350 volts and the percent regulation is 15%, what is the full-load output voltage?

45. A perfect power supply would have a 0% regulation. True or False?

46. The main purpose of a bleeder resistor is to (a) discharge the filter capacitors, (b) reduce the current drain on the power supply, (c) improve power supply regulation.

47. What is the value of the bleeder current in a 250-volt power supply equipped with a 10K bleeder resistor?

48. Assume a 450-volt power supply is connected to a load which draws 300 mA of current. The bleeder resistor has a resistance of 15,000 ohms. What is the total current drawn from the power supply?

the cold water pipe in just about every building. This is known as the ground side.) Thus, if you were to touch a water pipe, sink, radiator, etc., and the radio chassis, you would not receive a shock. Both the chassis and water pipe are at the same potential.

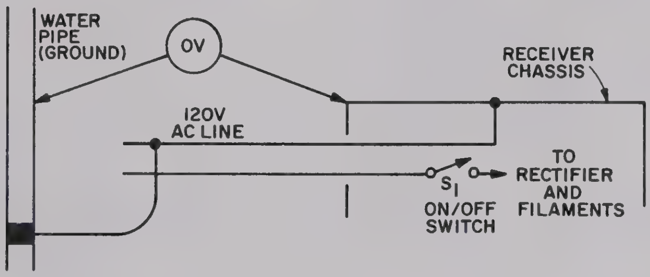


Figure 27

Now, suppose that the line cord is reversed (plug reversed), as shown in Figure 28. The ungrounded side of the ac line is now connected to the receiver chassis through S_1. With S_1 either closed or open, there is a difference in potential of 120 volts between the chassis and the water pipe. If you were to touch the chassis and water pipe, you would receive a severe or possibly even fatal shock.

The shock hazard is eliminated in a number of ways. For example, the cabinet may be made of plastic, wood, etc. The mounting screws and knobs are also insulated so that a person cannot come in contact with the chassis. In some cases a polarized plug is also used. The polarized plug can be inserted only one way into the ac receptacle, assuring that the chassis is always connected to the grounded side of the ac line. Remember this when you service this type of equipment. Make sure that all insulating components are in good order.

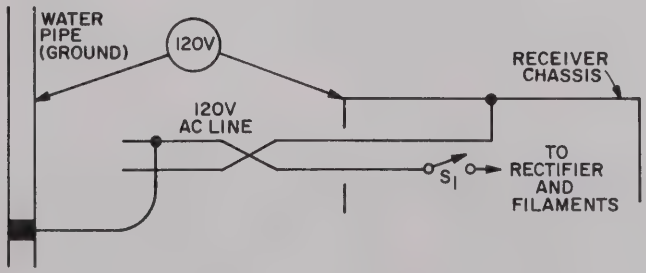


Figure 28

Voltage Multipliers

One of the disadvantages of the ac/dc supply is that its maximum output voltage is limited to about the peak value of the ac line voltage. This is because no power transformer is employed to step up the voltage. However, voltages higher than the peak of the ac line voltage can be obtained by using a **VOLTAGE MULTIPLIER** circuit.

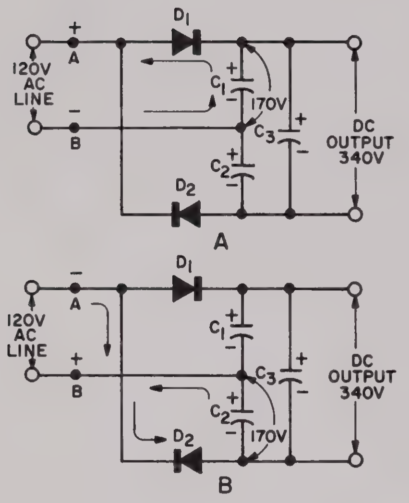


Figure 29

Figure 29 shows a voltage multiplier circuit called a **VOLTAGE DOUBLER.** As the name implies, this circuit provides a dc output voltage equal to twice the peak of the ac line voltage. Basically, the circuit consists of two half-wave rectifier circuits whose output voltages are added together.

To examine circuit operation, assume that point A is positive with respect to point B in Figure 29A. Under these conditions, the anode of D_1 is positive with respect to its cathode. At the same time, the cathode of D_2 is positive with respect to its anode. As a result, D_1 conducts and D_2 is cut off. With D_1 conductive, C_1 charges through D_1 to the peak of the ac line voltage.

On the other alternation of the ac line voltage, when point A is negative with respect to point B, the opposite conditions exist, as shown in Figure 29B. The anode of D_1 is negative with respect to its cathode, while the cathode of D_2 is negative with respect to its anode. As a result, D_1 is cut off and D_2 conducts. With D_2 conductive, C_2 charges through D_2 to the peak of the ac line voltage.

D_1 and D_2 conduct alternately and charge both C_1 and C_2 to the peak value of the ac line voltage. Notice the polarities of the voltages across C_1 and C_2. These two voltages are series aiding. The dc output voltage is therefore the sum of the voltages across C_1 and C_2, or two times the peak of the ac line voltage. The sum of the voltages across C_1 and C_2 appears across C_3, which provides filtering action. If additional filtering is required, any of the filter circuits shown earlier can be connected to the circuit.

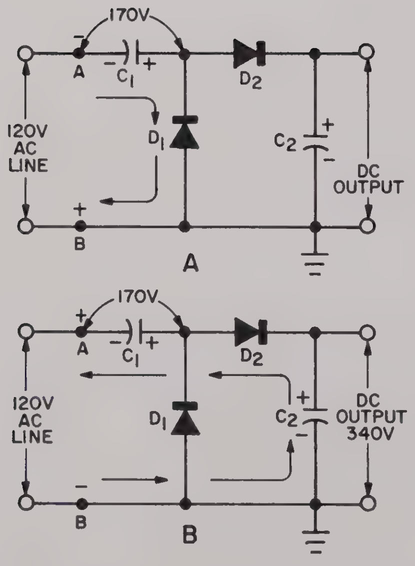
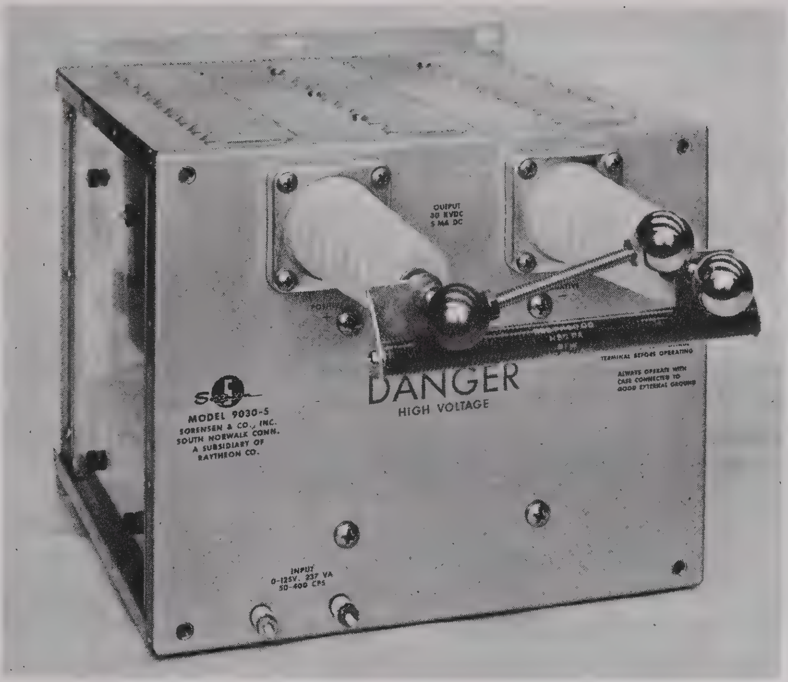


Figure 30

The voltage doubler shown in Figure 29 has one disadvantage. One side of the ac line is not the common output as in the ac/dc supply shown earlier. This can cause the generation of stray 60-Hz signals in the equipment and thus cause improper operation. Figure 30 shows another voltage doubler circuit which overcomes this problem. This circuit, like the one of Figure 29, consists of two separate rectifier circuits.



The special high-voltage power supply shown above can provide 30,000 volts at 5 mA.

Courtesy Raytheon Co.
Sorensen Operation

To examine circuit operation, assume that point A is negative with respect to point B in Figure 30A. Under these conditions, the cathode of D_1 is negative with respect to its anode. At the same time, the anode of D_2 is negative with respect to its cathode. Thus, D_1 conducts and D_2 is cut off. With D_1 conductive, C_1 charges to the peak of the ac line voltage (about 170V) through D_1.

On the other alternation of the ac line voltage, point A is positive with respect to point B, as shown in Figure 30B. Under these conditions, the cathode of D_1 is positive with respect to its anode. At the same time, the anode of D_2 is positive with respect to its cathode. Thus, D_1 is cut off and D_2 conducts. Since C_1 is in series with D_2 and the ac line voltage, the total voltage applied to D_2 is the ac line voltage plus the voltage across C_1. The voltage across C_1 is series aiding with the line voltage on this alternation. Therefore, C_2 charges to the peak of the line voltage plus the voltage across C_1. Since C_1 is charged to the peak of the line voltage, C_2 is charged to twice the peak of the line voltage.

Notice that, in Figure 30, one side of the ac line forms part of the dc output circuit. This side can be grounded as shown. The voltage doubler of Figure

30 is widely used in television receivers, especially the compact portables. Voltage multiplier circuits cannot, of course, operate from dc sources, but they are found in many power supplies that are either line-operated or transformer types. Because they are half-wave rectified, they cannot be used where either very smooth dc or high current is required.

VOLTAGE DIVIDERS

Frequently, it is desirable to obtain more than one dc output voltage from the same power supply. A number of output voltages can easily be obtained by connecting a number of resistors across the power supply terminals. An arrangement of this type is called a **VOLTAGE DIVIDER**. In addition, the voltage divider also serves as a bleeder resistor.

Figure 31 shows a power supply with a three-resistor voltage divider which provides three different output voltages. Output A is the power supply output terminal which supplies +300 volts. Output B supplies 250 volts and output C supplies 100 volts. These voltages are obtained by choosing the proper values for R_1, R_2 and R_3.

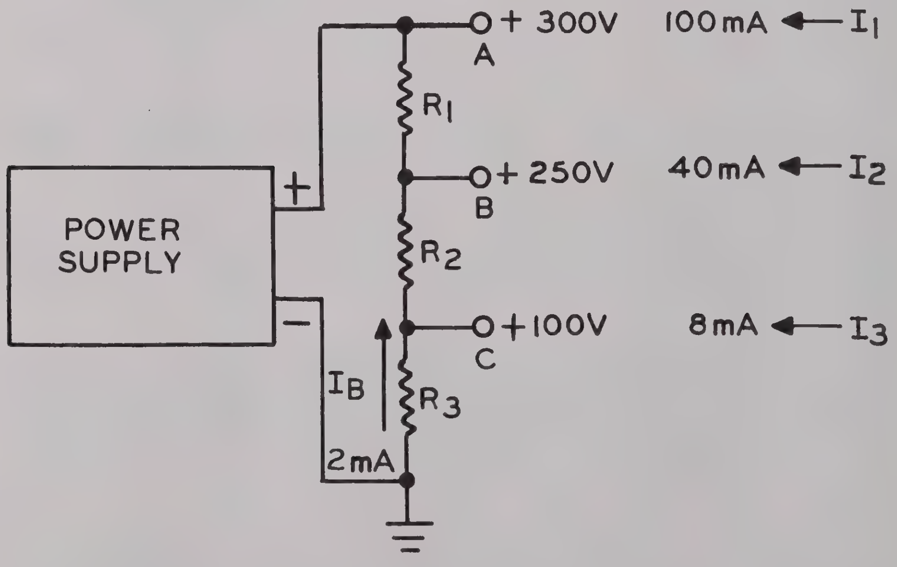


Figure 31

To choose the values of R_1, R_2 and R_3, the current required by the load connected to each terminal must be known. Typical values are shown in

Figure 31. To calculate the various resistors, start with the bottom resistor, R_3. Since this resistor does not carry any load current, its value is determined by assuming a small value of divider or bleeder current. In our examples, a bleeder current, I_B, of 2 mA is assumed. Since 100 volts appears between output C and ground, this is the voltage across R_3 and its value can be found by using Ohm's Law:

$$R_3 = \frac{E_{R_3}}{I_B} = \frac{100\text{V}}{2\ \text{mA}} = \frac{1 \times 10^2}{2 \times 10^{-3}} = \frac{1 \times 10^2 \times 10^3}{2}$$

$$= .5 \times 10^5 = 50{,}000, \text{ or } 50\ \text{k}\Omega.$$

Next, the value of R_2 is found. Since 100 volts must appear at output C and 250 volts appears at output B, R_2 must drop 150 volts. The current required at output C is 8 mA. Therefore, R_2 must carry $I_3 = 8$ mA plus the bleeder current, $I_B = 2$ mA. Therefore, the voltage across R_2 known, and the current known, Ohm's Law can be used to determine the value of R_2:

$$R_2 = \frac{E_{R_2}}{I_B + I_3} = \frac{150\text{V}}{2\ \text{mA} + 8\ \text{mA}} = \frac{1.5 \times 10^2}{1.0 \times 10^{-2}}$$

$$= \frac{1.5 \times 10^2 \times 10^2}{1}$$

$$= 1.5 \times 10^4 = 15{,}000, \text{ or } 15\ \text{k}\Omega.$$

Finally, the value of R_1 can be determined. Since 250 volts must appear at output B and 300 volts appears at output A, R_1 must drop 50 volts. The current required at output B is 40 mA. Therefore, R_1 must carry this current, $I_2 = 40$ mA, plus the 8 mA at output C, plus the 2 mA bleeder current. Using Ohm's Law, the value of R_1 is:

$$R_1 = \frac{E_{R_1}}{I_2 + I_3 + I_B} = \frac{50\text{V}}{40\ \text{mA} + 8\ \text{mA} + 2\ \text{mA}} = \frac{5 \times 10^1}{5 \times 10^{-2}}$$

$$= \frac{5 \times 10^1 \times 10^2}{5} = 1 \times 10^3 = 1000, \text{ or } 1\ \text{k}\Omega.$$

EQUIPMENT PROTECTION

Most electronic equipment requiring an appreciable amount of current has some type of fast-acting turn-off protection device. This protection device

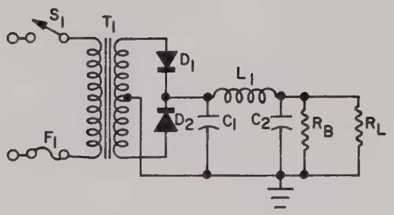


Figure 32

usually is a fuse. The fuse protects the equipment from heat damage caused by excessive current. The excessive current could be caused by a defective component causing a short circuit. Figure 32 shows a typical full-wave power supply with a fuse (F_1) placed in the primary circuit of the transformer, T_1.

If a fuse were not used, excessive current would eventually cause permanent damage to the power supply or other components in the equipment. The fuse current rating is slightly more than the normal current requirement for the equipment. For example, if the equipment normally requires a maximum line current of a little less than 3 amperes, a 3-ampere fuse should be used. If a fuse with a much lower current rating were used, it would open and turn off the equipment, even during normal operation. If a fuse with a much higher current rating were used, it might not open when excessive current is drawn. The equipment might then be damaged by the excessive current.

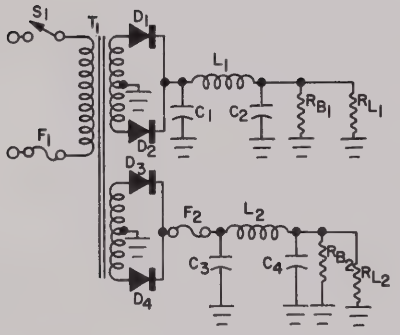


Figure 33

For further protection, a fuse could also be placed in a secondary circuit of T_1, as shown in Figure 33. Fuse F_2 adds a region of safety for the type of equipment it is protecting. F_2 would have a smaller current rating than F_1; however, it would have to be able to carry the normal circuit current for its circuit.

Some electronic equipment contains sophisticated, elaborate overload protection circuitry. Such circuitry is usually used where power must be removed almost instantaneously if component damage is to be avoided. Fuses require a length of time in which to open that is sometimes too long to prevent overload damage to some components. A transistorized protective circuit, however, can be designed so that it removes power only a few microseconds after the start of an excess current drain.

BATTERY CHARGING

As described earlier in this lesson, secondary cells such as the lead-acid and nickel-cadmium cells can be charged to restore their chemical action. The charging process consists of connecting the battery to a power supply and forcing electrons into the negative terminal and out the positive terminal. The simple half-wave rectifier can be used as a **BATTERY CHARGER**.

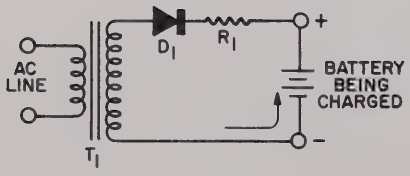


Figure 34

Figure 34 shows the circuit of a simple battery charger. Each time D_1 conducts, it forces current through the battery in the direction shown by the arrow. R_1 limits the charging current to the correct value. Generally, a battery or cell is charged at one tenth its ampere-hour rating. For example,

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TRANSFORMERLESS POWER SUPPLIES

AC/DC POWER SUPPLIES

VOLTAGE MULTIPLIERS

VOLTAGE DIVIDERS

EQUIPMENT PROTECTION

BATTERY CHARGING

49. Why is the circuit of Figure 26 called an ac/dc supply?

50. What is the name given to the filament circuit in Figure 26?

51. Suppose one of the tube filaments burns out (opens) in Figure 26. Would the other tube filaments still operate?

52. What is the effect in a piece of equipment using an ac/dc supply if the line cord is plugged in so that the chassis is connected to the ungrounded side of the ac line?

53. What is the advantage of the voltage doubler shown in Figure 29?

54. In the circuit of Figure 29, the dc output voltage is the sum of the voltages across C_1 and C_2. True or False?

55. What is the advantage of the voltage doubler shown in Figure 30 over the one shown in Figure 29?

56. C_2 in Figure 30 charges to (a) the peak of the ac line voltage, (b) one half of the peak of the ac line voltage, (c) twice the peak of the ac line voltage.

57. **Determine the value of the voltage divider resistors in Figure 31 if I_3 = 3 mA, I_2 = 20 mA and I_B = 2 mA.**

58. **What should be the charging current of a nickel-cadmium cell rated at 2 ampere-hours? How long should it be charged?**

a nickel-cadmium cell rated at 500 mA hours would be charged at 50 mA. Since more energy must be put back into the cell than was removed, the normal charging time is 14 to 16 hours at 1/10 the ampere-hour rating. This "puts back into the cell" 140 to 160 percent of the energy that was removed.

SUMMARY

For most portable applications, cells or combinations of cells (batteries) are used to supply the required dc operating voltages. Primary cells such as the zinc-carbon and most alkaline cells cannot be charged, whereas secondary cells such as lead-acid and nickel-cadmium cells can be charged and used over again.

Nonportable equipment is generally operated from the ac power line. The power supply circuit converts the ac line voltage into the required dc operating voltages. The power supply circuit consists of several sections. The rectifier converts the ac to pulsating dc. A transformer can be used to step up or step down the line voltage as needed. The pulsating dc from the rectifier is smoothed out by the filter circuit.

The full-wave and half-wave rectifiers are the two basic types of rectifier circuits. In the full-wave circuit, two pulses of current occur during each cycle of the supply, as compared to one pulse of current in the half-wave circuit. As a result, the full-wave circuit is easier to filter.

There are many types of filter circuits. Many circuits employ just a simple filter capacitor. Improved filtering is provided by using combinations of inductors and capacitors in π- and L-type filter circuits.

The rectifier and filter circuit can also be arranged so that it provides an output voltage which is a multiple of the source voltage. This permits high output voltages without the use of a transformer.

IMPORTANT DEFINITIONS

AMPERE-HOUR — A rating used to describe the capacity of a cell or battery. It is found by multiplying the discharge current of a cell or battery by the time required to discharge it to a certain output voltage.

BATTERY — A group of cells connected together. Sometimes the term battery is used to describe a single cell.

BATTERY CHARGER — A dc power supply used to supply current to a battery for charging purposes.

BLEEDER RESISTOR — A resistor which is used to draw a fixed current from a power supply.

BRIDGE RECTIFIER — A full-wave rectifier circuit that employs four diodes and does not require a center-tapped ac supply.

CAPACITOR INPUT — A type of power supply filter in which a capacitor is connected across the output of the rectifier.

CELL — An electric cell is a device that converts chemical, light, etc., energy into electric energy.

CHOKE — The filter inductor in a power supply.

CHOKE INPUT — A type of power supply filter in which a choke or filter inductor is connected to the output of the rectifier.

FILTER — The section of a power supply that smooths out the pulsating dc produced by the rectifier, and thus provides a smooth dc output.

FULL-WAVE RECTIFIER — A circuit which converts both alternations of an alternating current into a pulsating direct current.

HALF-WAVE RECTIFIER — A circuit which converts alternating current into pulsating direct current by conducting current during only one alternation of each cycle of the alternating current.

IMPORTANT DEFINITIONS (Continued)

PEAK INVERSE VOLTAGE (PIV) — The maximum voltage applied across the rectifier in a power supply when it is not conducting.

PI(π)-TYPE FILTER — A type of power supply filter employing two capacitors and a resistor or inductor connected in the shape of the Greek letter pi (π).

POWER SUPPLY — That section of a piece of electronic equipment which supplies the required dc operating voltages.

PRIMARY CELL — An electric cell in which the chemical action is not reversible. Once the materials in the cell are exhausted, the cell can no longer be used.

REGULATION — The ability of a power supply to maintain a constant output voltage under varying load conditions.

RIPPLE VOLTAGE — The alternating component of the dc output voltage of a power supply.

SECONDARY CELL — An electric cell in which the chemical action is reversible. After being discharged, the cell can be recharged by passing a current through it in the opposite direction.

SERIES STRING — An arrangement where tube filaments are series connected in a line-operated power supply.

VOLTAGE DIVIDER — A network used to obtain a number of dc voltages from a power supply.

VOLTAGE DOUBLER — A power supply circuit in which the dc output voltage is twice the peak value of the ac line voltage.

VOLTAGE MULTIPLIER — A power supply circuit in which the dc output voltage is several times the peak value of the ac supply voltage.

ESSENTIAL SYMBOLS AND EQUATIONS

E_F	Full-load output voltage
E_N	No-load output voltage

$$\% \text{ Regulation} = \frac{E_N - E_F}{E_F} \times 100 \qquad (1)$$

PRACTICE EXERCISE SOLUTIONS

1. A primary cell is one that cannot be used after the chemical action has used up the materials in the cell.

2. The emf is developed by ion flow to the electrodes. The positive ions make the positive electrode positive by attracting electrons. The negative ions add electrons to the negative plate.

3. mercury

4. 1.35 to 1.4 volts for the mercury cell and 1.4 to 1.5 volts for the alkaline cell.

5. longer

6. False — Some alkaline cells, however, can be recharged.

7. 2.1 volts for the lead-acid cell and 1.2 volts for the nickel-cadmium cell.

8. A lead-acid cell is charged by passing a current through it in the opposite direction.

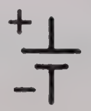
9. 45 ampere-hours. — The capacity is equal to the current in amperes times the discharge time in hours.

10. (b) the sum of the individual cell voltages.

11. 10.8 volts. — The sum of 9 cells connected in series is 1.2 × 9, or 10.8 volts.

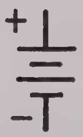
12. Three cells in series. — A single lead-acid cell develops 2.1 volts and three cells in series will produce 2.1 × 3, or 6.3 volts.

13.



PRACTICE EXERCISE SOLUTIONS (Continued)

14.



15. (b) the total available current is the sum of the current each cell can supply.

16. 2.1 volts. — Each cell develops 2.1 volts. When they are connected in parallel, the output voltage is the same as that of one cell.

17. The transformer steps up or steps down the ac line voltage, the rectifier converts the ac to pulsating dc and the filter smooths out the pulsating dc.

18. False — The output of the half-wave rectifier in Figure 13 is pulsating dc.

19. One. — A current pulse flows through the load when the anode of the rectifier diode is made positive with respect to the cathode.

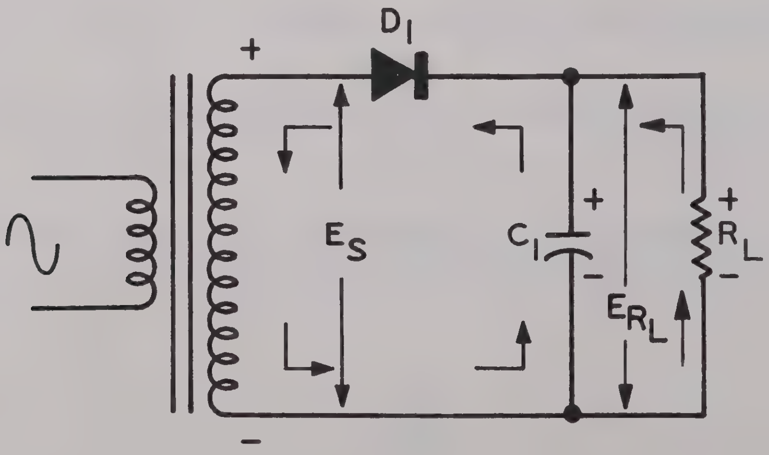
20. The full-wave rectifier produces two current pulses through the load during each cycle of the ac supply whereas the half-wave rectifier produces one.

21. The current pulses through R_L would be in the opposite direction, reversing the polarity of the voltage drop across R_L.

22. False — The bridge rectifier is a full-wave rectifier.

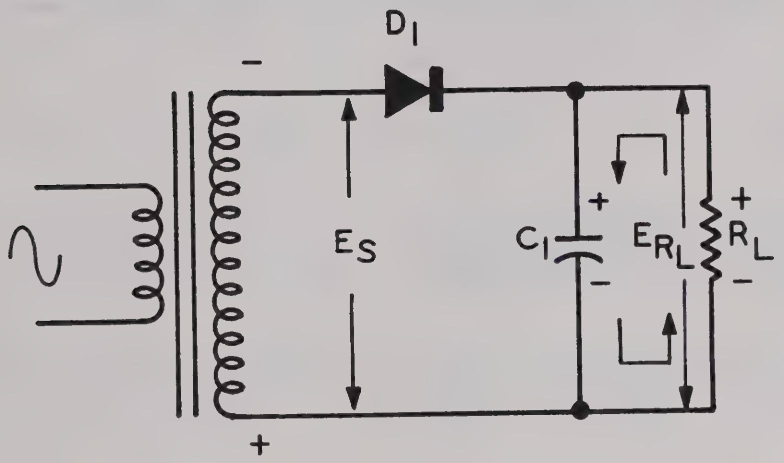
23. D_3 and D_4.

24.

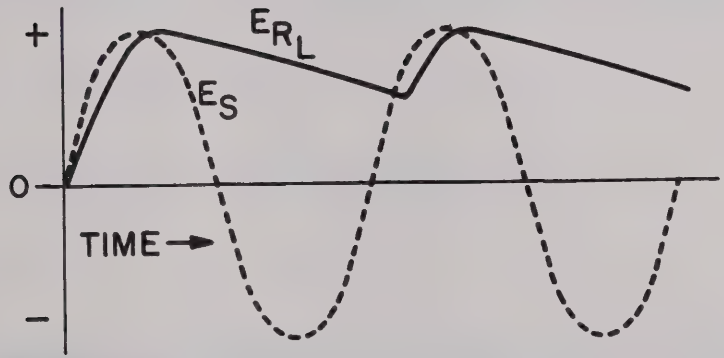


PRACTICE EXERCISE SOLUTIONS (Continued)

25.



26.



27. ripple voltage

28. The ripple voltage amplitude would reduce because the charge on the capacitor would not decrease as much between charge periods.

29. The PIV rating.

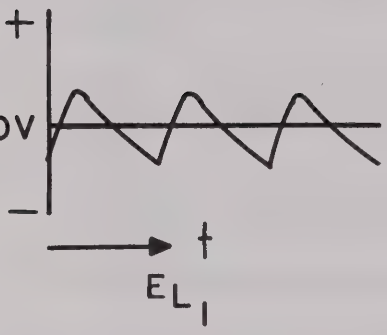
30. False — Referring back to Question 28, less ripple voltage will be present when the load current is small.

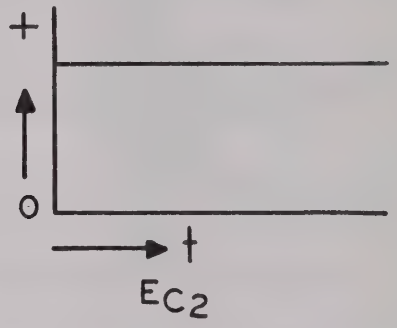
31. True — A half-wave power supply conducts once during each cycle, whereas a full-wave power supply conducts twice during each cycle.

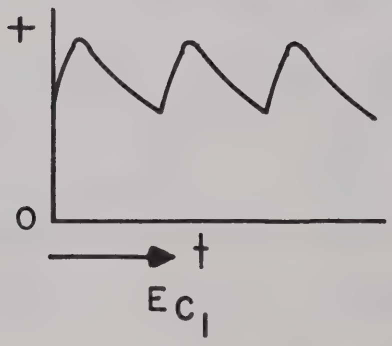
PRACTICE EXERCISE SOLUTIONS (Continued)

32. True — There is a shorter interval for filter capacitor discharge in a full-wave power supply; consequently, the ripple voltage is smaller.

33.







34. The dc voltage drop across a choke is normally much less than across a resistor. However, a resistor is less expensive, smaller and lighter in weight than a choke.

35. True — The ripple voltage amplitude reduces because the charge on the capacitor would not decrease as much between charge periods.

36. False — A diode will conduct only when its anode is positive with respect to its cathode. Since the filter capacitor never completely discharges between cycles, a positive voltage always appears on the diode cathode. The diode will conduct only on positive peaks of the applied voltage when the applied voltage is more positive than the filter capacitor voltage on its cathode.

37. π-type capacitor input filter.

PRACTICE EXERCISE SOLUTIONS (Continued)

38. Choke input filter.

39. A capacitor input filter provides higher output voltage.

40. A choke input filter provides better regulation.

41. (b) regulation. — A power supply could have good filtering and hence very low ripple voltage, and yet have poor regulation. The reverse is also true.

42. (b) decrease. — An increase of load current causes a greater voltage loss across the resistances of the filter choke or resistor, the diode, and the transformer winding.

43. Use high-capacitance filter capacitors, a high-inductance choke, and select a rectifier, choke and power transformer with low resistances.

44. 304V. — Rearranging Formula 1 to find E_F yields:

$$E_F = \frac{E_N}{Reg + 1} = \frac{350}{.15 + 1} = \frac{350}{1.15} = 304 \text{ volts.}$$

45. True

46. (c) improve power supply regulation. — The bleeder also discharges the filter capacitors, but this is secondary in importance. Since many power supplies do not have bleeder resistors, you should make a habit of always discharging the filters before attempting to work on the equipment.

47. 25 mA. — By Ohm's Law, the bleeder current $I = \frac{E}{R} = \frac{250}{10{,}000} = .025$ ampere, or 25 mA.

48. 330 mA. — The bleeder current $I = \frac{E}{R} = \frac{450}{15{,}000} = .03$A, or 30 mA.

The total current is equal to the sum of the load current and the bleeder current: 300 + 30 = 330 mA.

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ONE OF THE
BELL & HOWELL SCHOOLS

1040A & B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1040B

1. D - ALKALINE AND MERCURY CELLS -- ARE DESIGNED FOR CONTINUOUS DUTY.
The construction of the alkaline and mercury cells are such that they can provide power continuously, whereas the zinc carbon cells drop off in continuous service.

2. A - THE CAPACITY OF A LEAD ACID CELL THAT CAN DELIVER 2 AMPERES FOR 20 HOURS IS -- 40 AMPERE HOURS.
The ampere hour rating is found by multiplying the current by the time it is drawn: 2A × 20 hours = 40 ampere hours.

3. A - THE RECTIFIER IN A POWER SUPPLY -- CONVERTS THE AC LINE VOLTAGE TO PULSATING DC.
The filter system in the power supply smooths out the pulsating dc.

4. A - IN THE POWER SUPPLY OF FIGURE 19 -- C_1 SUPPLIES CURRENT TO THE LOAD WHEN D_1 IS CUT OFF.
When D_1 conducts it charges C_1 and supplies load current.

5. A - INCREASING THE CAPACITANCE VALUE OF THE FILTER CAPACITOR IN A POWER SUPPLY -- REDUCES THE RIPPLE VOLTAGE AMPLITUDE.
Increasing the capacitance value of the capacitor allows it to store more energy and thus it does not discharge to as low a voltage during the time the rectifier is cut off.

6. B - TO OBTAIN GOOD POWER SUPPLY REGULATION, -- THE POWER SUPPLY SHOULD HAVE A LOW INTERNAL RESISTANCE.
A low internal resistance is obtained by employing low forward resistance diodes and a transformer with low resistance windings.

7. C - THE CIRCUIT OF FIGURE 18 -- IS A BRIDGE RECTIFIER.
The bridge rectifier provides full wave rectification without the need for a center tapped transformer.

8. C - IN THE CIRCUIT OF FIGURE 31, IF THE EXTERNAL CIRCUIT CONNECTED TO POINT B OPENS -- THE VOLTAGE AT POINT B WILL INCREASE.
With the circuit at point B open, I_2 will be zero, reducing the current through R_1 and increasing the voltage at point B.

9. C - WITH THE POWER SUPPLY CONNECTED AS SHOWN IN FIGURE 28 -- THE CHASSIS IS "HOT" WITH RESPECT TO GROUND.
To reduce the shock hazard, the connections to the line must be reversed as shown in Figure 27.

10. B - THE ADDITION OF A BLEEDER RESISTOR TO A POWER SUPPLY -- IMPROVES REGULATION.
The regulation is improved since the bleeder resistor reduces the no load output voltage.

1040A

All explanations are the same as for 1040B except for those given below.

4. A - IN THE POWER SUPPLY OF FIGURE 18 -- C_1 SUPPLIES CURRENT TO THE LOAD WHEN D_1 IS CUT OFF.
When D_1 conducts it charges C_1 and supplies load current.

7. C - THE CIRCUIT OF FIGURE 24 -- IS A BRIDGE RECTIFIER.
The bridge rectifier provides full wave rectification without the need for a center tapped transformer.

8. C - IN THE CIRCUIT OF FIGURE 30, IF THE EXTERNAL CIRCUIT CONNECTED TO POINT B OPENS -- THE VOLTAGE AT POINT B WILL INCREASE.
With the circuit at point B open, I_2 will be zero, reducing the current through R_1 and increasing the voltage at point B.

9. C - WITH THE POWER SUPPLY CONNECTED AS SHOWN IN FIGURE 27 -- THE CHASSIS IS "HOT" WITH RESPECT TO GROUND.
To reduce the shock hazard, the connections to the line must be reversed as shown in Figure 26.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1040B

Example: A ☐ B ☐ C ☐ D ■ A motorist may proceed across an intersection when the traffic light is

A. blue. B. red. C. black. D. green.

1. A ☒ B ☐ C ☐ D ☐ **Alkaline and mercury cells**
(A) are designed for only intermittent duty. (B) have a very short shelf life. (C) cannot provide as much output current as a comparable zinc-carbon cell. (D) are designed for continuous duty.

2. A ☒ B ☐ C ☐ D ☐ **The capacity of a lead-acid cell that can deliver 2 amperes for 20 hours is**
(A) 40 ampere-hours. (B) 20 ampere-hours. (C) 20 amperes. (D) 10 amperes.

3. A ☒ B ☐ C ☐ D ☐ **The rectifier in a power supply**
(A) converts the ac line voltage to pulsating dc. (B) converts the dc line voltage to ac. (C) smooths the pulsating dc developed by the circuit. (D) is always a semiconductor diode.

4. A ☒ B ☐ C ☐ D ☐ **In the power supply of Figure 19,**
(A) C_1 supplies current to the load when D_1 is cut off. (B) C_1 discharges when D_1 conducts. (C) C_1 discharges through D_1 and the T_1 secondary. (D) D_1 conducts for the entire positive alternation.

5. A ☒ B ☐ C ☐ D ☐ **Increasing the capacitance value of the filter capacitor in a power supply**
(A) reduces the ripple voltage amplitude. (B) has no effect on the ripple voltage amplitude. (C) decreases the current capacity of the supply. (D) provides poorer filtering.

6. A ☐ B ☒ C ☐ D ☐ **To obtain good power supply regulation,**
(A) diodes with a high forward resistance should be used. (B) the power supply should have a low internal resistance. (C) a filter inductor with a high internal resistance should be used. (D) the power transformer should have high resistance windings.

7. A ☐ B ☐ C ☒ D ☐ **The circuit of Figure 18**
(A) is a half-wave rectifier. (B) employs a pi-type filter. (C) is a bridge rectifier. (D) employs an L-type filter.

8. A ☐ B ☐ C ☒ D ☐ **In the circuit of Figure 31, if the external circuit connected to point B opens,**
(A) I_B will decrease. (B) the voltage at point B will decrease. (C) the voltage at point B will increase. (D) the voltage at point A will decrease.

9. A ☐ B ☐ C ☒ D ☐ **With the power supply connected as shown in Figure 28,**
(A) no shock hazard exists. (B) the chassis and ground are at the same potential. (C) the chassis is "hot" with respect to ground. (D) the chassis is isolated from the ac line.

10. A ☐ B ☒ C ☐ D ☐ **The addition of a bleeder resistor to a power supply**
(A) increased the output voltage. (B) improves regulation. (C) increases the percentage of regulation. (D) reduces the ripple voltage.

EXPERIMENT 6

POWER SUPPLIES

PARTS NEEDED

1 - Design Console
1 - Multimeter and Test Leads
- Modular Connectors
1 - 1 kΩ, 1/2 W, Resistor
1 - 3.9 kΩ, 1/2 W, Resistor
1 - 4.7 kΩ, 1/2 W, Resistor
2 - 10 kΩ, 1/2 W, Resistors
1 - 22 kΩ, 1/2 W, Resistor
1 - 100 kΩ, 1/2 W, Resistor
2 - Diodes
2 - 10 μF Capacitors
1 - 1000 μF Capacitor
2 - Test Prod Spring Adapters
- Hookup wire

OBJECTIVE

The purpose of this experiment is to analyze a half wave and full wave rectifier circuit, and compare the filtering and regulation characteristics of the two circuits; to investigate a voltage doubler circuit; and to investigate voltage divider circuits.

PART 1

PROCEDURE

HALF WAVE RECTIFIER

1. Set up the circuit shown in Figure 6-1.

2. Turn the design console on/off switch to the on position and measure the dc voltage across resistor R_1. Record this measurement in Table 6-1 in the HALF WAVE section, under dc and NO FILTER.

3. Place the red test prod in the output jack of the meter and measure the ac voltage across R_1. The output jack is used whenever an ac voltage is measured and a dc voltage is also present. If the normal meter jack is used the dc voltage will affect the meter; this then would present an erroneous value. Record the voltage you obtain in the HALF WAVE section of Table 6-1 under ac and NO FILTER. Turn the design console on/off switch to the off position.

4. Add a 10 μF capacitor in parallel with R_1 to form the circuit shown in Figure 6-2. This capacitor will filter the output voltage of the circuit. Turn the design console on/off switch to the on position and measure the dc voltage across the capacitor. Record the voltage in the HALF WAVE section of Table 6-1 under dc and 10 μF FILTER. The voltage should be much higher than that measured in Step 2.

5. Again using the output jack of the meter, measure the ac voltage in the output. Record your measurement in Table 6-1 in the HALF WAVE section under ac and 10 μF FILTER. The ac voltage should be less than that obtained in Step 3. Turn the design console on/off switch to the off position.

6. Replace C_1 with a 1000 μF capacitor. Turn the design console on/off switch to the on position and measure the dc voltage across R_1. Record the voltage in Table 6-1 in the HALF WAVE section under dc and 1000 μF FILTER. The measurement should be higher than that measured in either Step 2 or Step 4.

7. Measure the ac voltage present in the output, and record this value in Table 6-1 in the HALF WAVE section under ac and 1000 μF FILTER. The voltage will be very close or equal to zero. Turn the design console on/off switch to the off position.

CONCLUSION

We see in this experiment that, as the filter capacitor value is increased, the dc output voltage increases and the ac voltage (ripple) decreases.

PART 2

PROCEDURE

FULL WAVE RECTIFIER

1. Set up the circuit shown in Figure 6-3.

2. Turn the design console on/off switch to the on position and measure the dc output voltage. Record the value in the FULL WAVE section of Table 6-1 under dc and NO FILTER.

3. Measure the ac voltage across R_1 (use the output jack) and record the value in the FULL WAVE section of Table 6-1 under ac and NO FILTER.

4. Compare the ac and dc voltages obtained with the corresponding voltages of the half wave circuit. The dc output should be higher in the full wave circuit, since we are now utilizing the full ac input cycle. Also, the ac voltage should be lower; the difference will not be as great as the difference in dc voltage. Turn the design console on/off switch to the off position.

5. Add a 10 μF capacitor across R_1 to form the circuit shown in Figure 6-4.

6. Turn the design console on/off switch to the on position and measure the dc voltage across R_1. Record the voltage in Table 6-1 in the FULL WAVE section under dc and 10 μF FILTER. Your measurement should be higher than that of

Step 2.

7. Measure the ac voltage across R_1, and record the value in Table 6-1 in the FULL WAVE section under ac and 10 μF FILTER. The value should be lower than that measured in Step 3. Turn the design console on/off switch to the off position.

8. Replace the 10 μF capacitor with a 1000 μF capacitor. Turn the design console on/off switch to the on position and measure the dc voltage across R_1. Record the value in Table 6-1 in the FULL WAVE section under dc and 1000 μF FILTER.

9. Measure the ac voltage across R_1, and record the value in Table 6-1 in the FULL WAVE section under ac and 1000 μF FILTER. Turn the design console on/off switch to the off position.

CONCLUSION

The full wave circuit is easier to filter than the half wave circuit. It produces a higher dc output voltage with less filtering as shown when the 10 μF capacitor was used. In general, the full wave circuit will produce a higher output voltage with less filtering than a half wave circuit.

PART 3

PROCEDURE

REGULATION - HALF WAVE RECTIFIER

1. Set up the circuit shown in Figure 6-5.

2. The percentage of regulation will vary, depending on the value of filter capacitor and the value of load resistance. Table 6-2 has two columns under HALF WAVE rectifiers; one where 10 kΩ is considered full load and one where 1 kΩ is considered full load. The no load voltage is determined with no resistor in the circuit, as shown in Figure 6-5. Turn the design console on/off switch to the on position and measure the no load voltage. Record the voltage value in Table 6-2 in both HALF WAVE columns under NO LOAD VOLTAGE. Turn the design console on/off switch to the off position.

3. Install a 10 kΩ resistor in parallel with C_1. Turn the design console on/off switch to the on position and measure the full load voltage. Record the FULL LOAD VOLTAGE in Table 6-2 in the HALF WAVE column under LOAD 10 kΩ. Turn the design console on/off switch to the off position.

4. Using the data found in Steps 2 and 3, calculate the percentage of regulation for the 10 kΩ load resistance.

5. Replace the 10 kΩ resistor with a 1 kΩ resistor. Turn the design console on/off switch to the on position and measure the FULL LOAD VOLTAGE. Record the voltage in Table 6-2 in the HALF WAVE column under LOAD 1 kΩ. Turn the design console on/off switch to the off position.

6. Using the voltage obtained in Steps 2 and 5, calculate the percentage of regulation and record the result in Table 6-2 under the 1 kΩ load.

7. Replace the 10 μF capacitor with a 1000 μF capacitor and remove the load resistor. Turn the design console on/off switch to the on position and measure the no load voltage. Record the voltage in Table 6-3 in both HALF WAVE columns under NO LOAD VOLTAGE. Turn off the design console.

8. Insert the 10 kΩ resistor and turn the design console on/off switch to the on position. Measure the full load value and record this voltage in Table 6-3 in the HALF WAVE column under LOAD 10 kΩ. Turn the design console on/off switch to the off position and insert the 1 kΩ resistor. Turn the design console on/off switch to the on position and measure the full load value. Record it in Table 6-3. Calculate the percentage of regulation in each case and record the results in Table 6-3 under the appropriate load. Turn the design console on/off switch to the off position.

CONCLUSION

The values of both the load and the filter capacitor affect the percentage of regulation. The larger the load resistor, the better the regulation and the larger the filter capacitor, the better the regulation.

PART 4

PROCEDURE

REGULATIVE FULL WAVE RECTIFIER

1. Set up the circuit shown in Figure 6-6.

2. Use the same procedure as outlined in Steps 2 through 6 in Part 3. Measure the no load and full load voltages, using a 10 kΩ and a 1 kΩ resistor as the full load conditions. Record your results in Table 6-2 in the FULL WAVE columns under the appropriate loads. Calculate the percentage of regulation in both cases and record the results in Table 6-2 under the appropriate load. Turn the design console on/off switch to the off position.

3. Replace the 10 μF capacitor with a 1000 μF capacitor and, following the same procedure as in Steps 7 and 8 of Part 3, measure the values necessary for Table 6-3. Record the values in Table 6-3 under the appropriate loads in the FULL WAVE section. Calculate the percentages of regulation and record them in Table 6-3 under the appropriate loads. Turn the design console on/off switch to the off position.

CONCLUSION

By comparing Tables 6-2 and 6-3, you should notice that the percentage of regulation changes with both load resistance changes and filter capacitor changes. Also the percentage of regulation of the full wave circuit is generally better than the half wave circuit with the same load and filter capacitor values.

PART 5

PROCEDURE

VOLTAGE DOUBLERS

1. Set up the circuit shown in Figure 6-7. Be sure to observe the polarity of all of the parts. Turn the on/off switch of the design console to the on position.

2. Measure the ac voltage applied to the circuit between terminals 2 and 10 of the transformer. Using this value, calculate the peak of the applied voltage. Record your calculated value.

10.6 volts peak

3. Measure the dc voltage across C_1. The value should be approximately equal to the peak of the applied voltage calculated in Step 2. Record your measurement below.

10 - volts

4. Measure the dc voltage across C_2. The value you obtain should be approximately two times the value measured in Step 3. Record your measurement below.

21 volts

Capacitor C_1 and diode D_1 form a half wave rectifier circuit. C_1 will charge to the peak of the applied voltage, just as in a conventional half wave rectifier. The voltage across this capacitor will then add to the applied voltage when the polarity of the applied ac is such that D_1 will not conduct. D_2 will conduct when D_1 is not conducting, charging C_2 to the sum of the voltage across C_1 and the applied voltage. Turn the design console on/off switch to the off position.

5. Connect a 4.7 kΩ resistor across capacitor C_2. This resistor will serve as a load for the circuit. Turn the design console on/off switch to the on position and measure the voltage across the resistor. Record the value below. Turn the design console on/off switch to the off position.

14.5 volts

6. Using the no load value measured in Step 4 and the full load voltage measured in Step 5, calculate the percentage of regulation. Record your result below.

$\frac{21-14.5}{21} = \frac{6.5}{21}$

31 % Reg.

CONCLUSION

This circuit has poor regulation characteristics, since the output voltage depends on the charge retained by C_1. As the load current increases, C_1 discharges farther and less voltage is applied to charge C_2.

PART 6

PROCEDURE

VOLTAGE DIVIDERS

1. Set up the circuit shown in Figure 6-8.

2. Turn the design console on/off switch to the on position and measure the voltages at points A, B and C (with respect to ground). Record the values below.

Point A 10 volts

Point B 6.4 volts

Point C 4.2 volts

3. Turn the design console on/off switch to the off position and remove resistor R_4 from the circuit. Turn the design console on/off switch to the on position. Remeasure the voltages at points A, B and C (with respect to ground). Record the values below.

Point A 10 volts

Point B 6.5 volts

Point C 4.5 volts

4. Turn the design console on/off switch to the off position. Replace R_4 and remove R_5. Turn the design console on/off switch to the on position and measure the voltages at points A, B and C (with respect to ground). Record your results below.

Point A 10 volts

Point B 8.7 volts

Point C 5.7 volts

Turn the design console on/off switch to the off position.

5. Replace R_5 in the circuit. Turn the design console on/off switch to the on position. Measure and record the following currents.

I_{R1} .87 mA

I_{R2} .23 mA

I_{R3} .19 mA

I_{R4} .04 mA

I_{R5} .60 mA

I_{R6} 2.5 mA

Turn the design console on/off switch to the off position.

6. Using the above values, verify the following equations:

$$I_{R2} = I_{R3} + I_{R4}$$

$$I_{R1} = I_{R2} + I_{R5}.$$

CONCLUSION

The current through R_3 consists only of bleeder current. This current plus the current through R_4 make up the current through R_2. I_{R2} plus the current through R_5 make up the current through R_1.

When the various loads are removed, the voltage at the various points should increase, except at point A where the total applied voltage is measured. For example, when R_5 is removed, the current through R_1 will decrease. With less current through the resistor, there will be less voltage dropped; therefore, more voltage will appear at point B. (Note: When removing a high resistance load, the change in current may be so small that the increase of voltage may be difficult to spot.)

The current through R_6 does not make up any part of the R_1, R_2 or R_3 current, but will add to the total current.

CIRCUIT	HALF WAVE		FULL WAVE	
VOLTAGE TYPE	DC	AC	DC	AC
NO FILTER	3.2	3,6	6.3	3,3
10 μF FILTER	6.8	1,6	8,6	,8
1000 μF FILTER	10	0	9,8	0

COMPARISON OF FILTERING: HALF WAVE - FULL WAVE

TABLE 6-1

CIRCUIT	HALF WAVE		FULL WAVE	
NO LOAD VOLTAGE	10	10	10	10
LOAD	10 kΩ	1 kΩ	10 kΩ	1 kΩ
FULL LOAD VOLTAGE	9,6	7,8	9,9	8,6
% REGULATION	4%	22%	1%	14%

COMPARISON OF REGULATION: HALF WAVE - FULL WAVE USING 10 μF FILTER

TABLE 6-2

CIRCUIT	HALF WAVE		FULL WAVE	
NO LOAD VOLTAGE	10	10	10	10
LOAD	10 kΩ	1 kΩ	10 kΩ	1 kΩ
FULL LOAD VOLTAGE	10	9,8	10	9,9
% REGULATION	0%	2%	0%	1%

COMPARISON OF REGULATION: HALF WAVE - FULL WAVE USING 1000 μF FILTER

TABLE 6-3

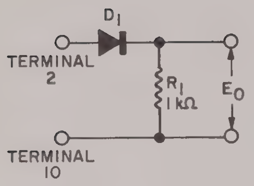

FIGURE 6-1

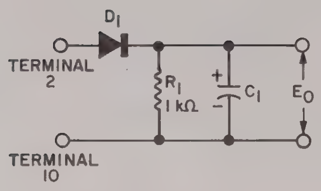

FIGURE 6-2

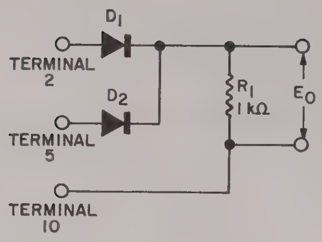

FIGURE 6-3

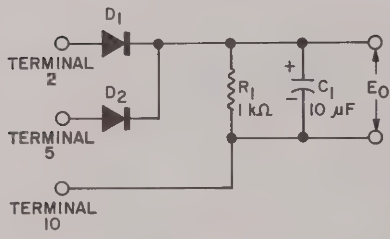

FIGURE 6-4

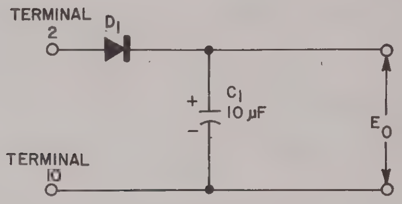

FIGURE 6-5

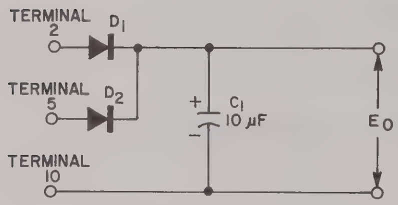

FIGURE 6-6

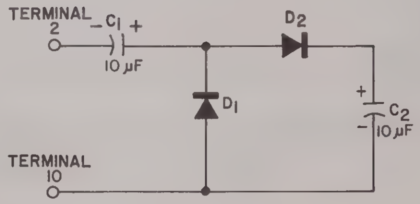

FIGURE 6-7

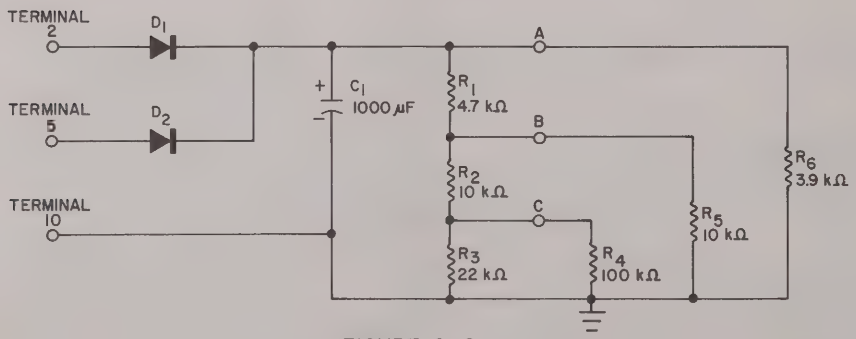

FIGURE 6-8

DE VRY INSTITUTE OF TECHNOLOGY
4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

9502-6A
EXAMINATION CHECK SHEET

1. A - REFERRING TO TABLE 6-1, WHICH TYPE OF CIRCUIT GAVE THE BEST FILTERING WITH THE 10 μF FILTER? -- FULL WAVE.
Your measurements should show answer A as correct. If not redo the experiment.

2. A - REFERRING TO TABLE 6-1, WHICH CIRCUIT PRODUCED THE HIGHEST AC OUTPUT? -- HALF WAVE WITH NO FILTER.
The half wave supply has the greatest ac output. The experiment should prove this statement.

3. B - REFERRING TO TABLE 6-2, WHICH CIRCUIT PRODUCED THE WORST OVERALL PERCENTAGE OF REGULATION? -- HALF WAVE.
The half wave supply has the worst regulation.

4. B - INCREASING THE VALUE OF THE FILTER CAPACITOR WILL CAUSE THE PERCENTAGE OF REGULATION TO -- DECREASE.
Adding filtering (such as increasing the capacitance of the filter capacitor) will decrease the percentage of regulation. The best regulation is 0 percent.

5. A - IN TABLE 6-2 WHICH CIRCUIT PRODUCED THE BEST OVERALL PERCENTAGE OF REGULATION? -- FULL WAVE.
The full wave circuit will produce the best percentage of regulation in comparison to equal conditions using a half wave rectifier.

6. B - COMPARING TABLES 6-2 AND 6-3, WHICH FILTER PRODUCED THE BEST OVERALL PERCENTAGE OF REGULATION? -- 1000 μF.
The higher value filter capacitor will produce the best percentage of regulation with other factors remaining the same.

7. A - IN THE HALF WAVE CIRCUIT, WHICH VALUE OF LOAD RESISTOR CAUSED THE WORST PERCENTAGE OF REGULATION? -- 1 kΩ.
The lower value of the resistance will load the circuit to a greater extent, therefore increasing the percentage of regulation.

8. C - IN FIGURE 6-7 WHAT IS THE VOLTAGE ACROSS C_1? -- EQUAL TO THE PEAK OF THE SUPPLIED VOLTAGE.
The capacitor will charge to the peak of the supply voltage when D_1 conducts.

9. A - IN FIGURE 6-8 WHICH POINT IS AT THE HIGHEST POTENTIAL? -- POINT A.
Point A with respect to ground is across the entire supply, therefore will have the highest voltage.

10. A - IN FIGURE 6-8 IF RESISTOR R_4 OPENS, WHAT EFFECT DOES THIS MALFUNCTION HAVE ON THE VOLTAGE AT POINT C? -- INCREASES.
The open resistor will reduce the current through R_2, reducing the voltage across R_2. There will be more voltage, then, at Point C.

TRANSISTOR OPERATION

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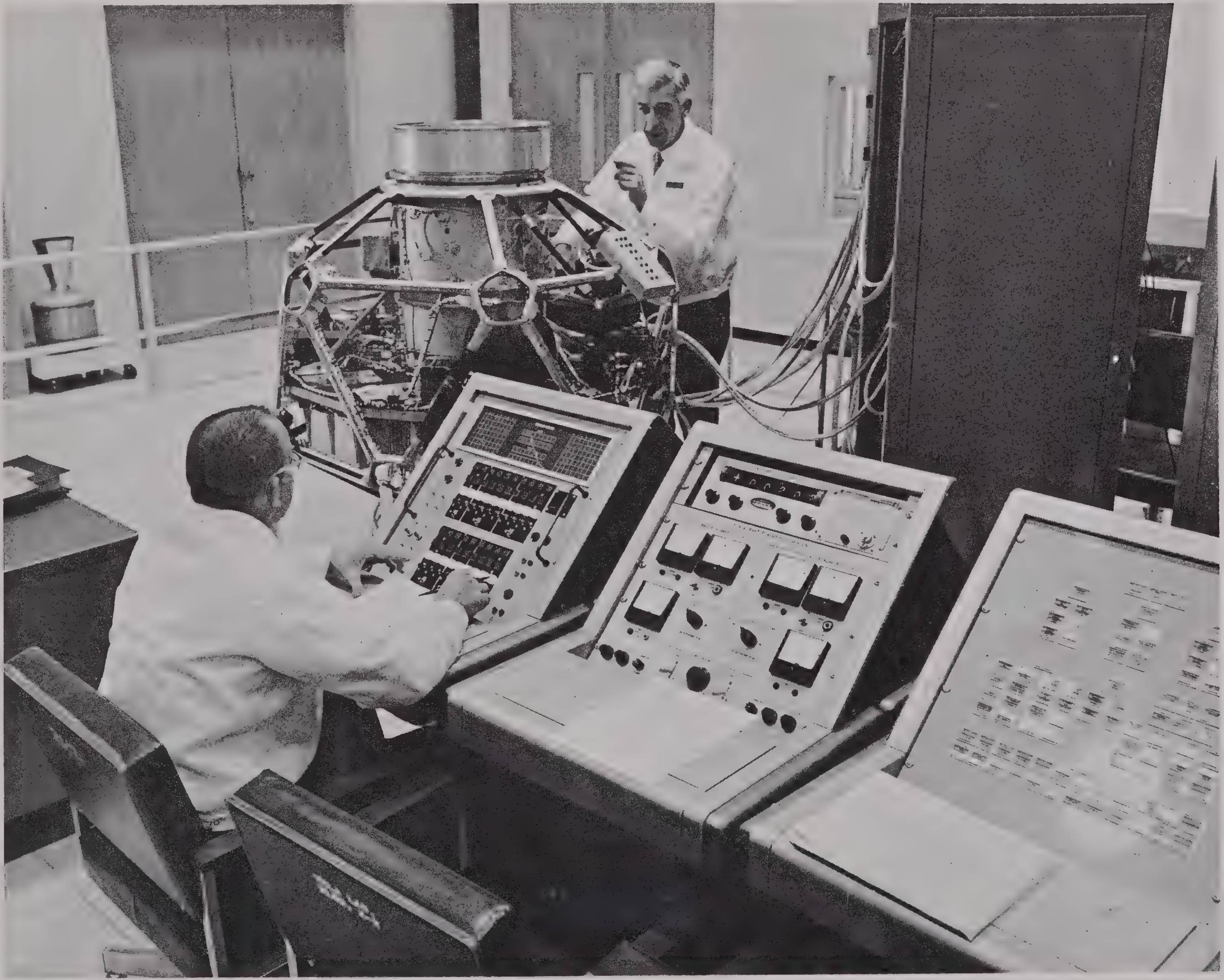

The development of the transistor opened the door to many new fields. For example, the satellite shown above would not have been possible without the transistor.

Courtesy TRW Inc.

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> *The only limit to our realization of tomorrow*
> *will be our doubts of today.*
> *—Franklin D. Roosevelt*

TRANSISTOR OPERATION

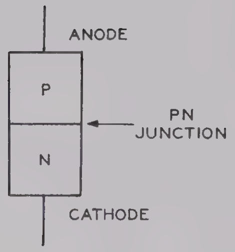


Figure 1

The **TRANSISTOR** is the one device most responsible for the rapid advances in the field of electronics. Due to its small size, high efficiency and low cost, it has replaced the vacuum tube in most applications. Many of the items we take for granted today, such as pocket radios, high-speed computers, communications satellites, etc., would not be practical without the transistor.

BASIC TRANSISTOR OPERATION

Transistors, like semiconductor diodes, are made of silicon or germanium material. As in a semiconductor diode, the silicon or germanium material is doped to produce N- or P-type semiconductor material. While the diode serves as a switch (open or closed circuit), the transistor functions as a current control device. That is, the current can be varied from near zero to some maximum value.

Let's briefly review the action in a diode. Figure 1 shows a semiconductor diode. The P-type material contains HOLES, or an absence of electrons, and the N-type material contains an excess of ELECTRONS. When the diode is formed, the holes and electrons near the PN junction combine. The recombination at the junction makes the P-type material slightly negative near the junction and the N-type material slightly positive near the junction. This action sets up a "potential hill" or "barrier" to prevent further recombination. When the diode is FORWARD biased (N-type material negative and P-type material positive), the barrier is overcome and the diode conducts current. However, when the diode is REVERSE biased (N-type material positive and P-type material negative), the barrier is aided and only a small reverse current flows. The term **MAJORITY CARRIERS** is used to describe the holes that flow in the P-type material and the electrons that flow in the N-type material during forward bias conditions. During reverse bias conditions, holes flow in the N-type material, and electrons flow in the P-type material. Under these conditions, the holes and electrons are referred to as **MINORITY CARRIERS**.

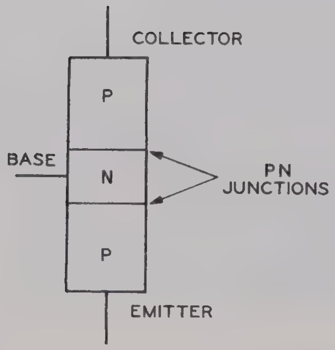


Figure 2

Figure 2 shows the basic construction of the **BIPOLAR JUNCTION TRANSISTOR**. Like the diode of Figure 1, the transistor is constructed of P- and N-type semiconductor material. However, the transistor employs three sections of semiconductor material. This results in two PN junctions. The connections to the semiconductor regions are referred to as the **COLLECTOR, BASE** and **EMITTER**, as shown in Figure 2. The PN junction between the base and collector regions is referred to as the **COLLECTOR**

JUNCTION. The PN junction between the base and emitter regions is referred to as the **EMITTER JUNCTION**.

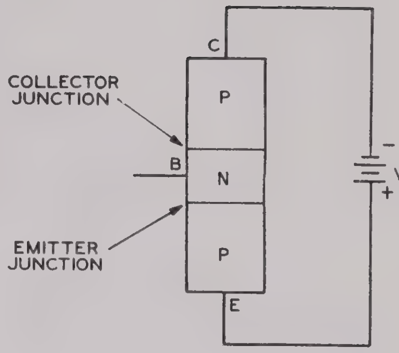


Figure 3

To illustrate transistor action, suppose the transistor of Figure 2 is connected to a voltage source, V_S, as shown in Figure 3. (Note: The letter V is normally used to indicate voltage in transistor circuits.) The letters C, B and E represent the connections to the collector, base and emitter regions, respectively. Under the conditions shown in Figure 3, practically no current flows through the transistor. Reversing the polarity of V_S does not affect the action. The transistor still does not conduct any appreciable amount of current.

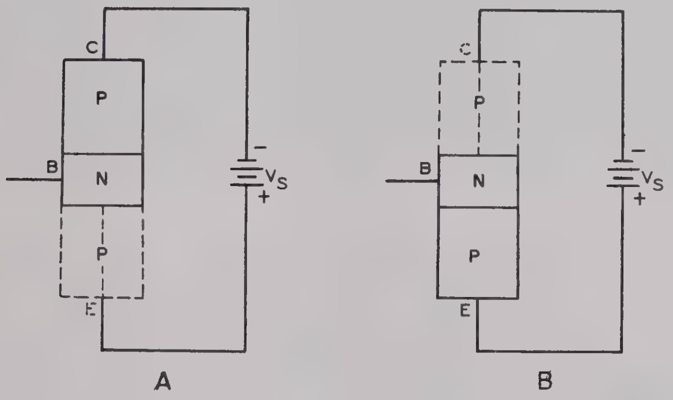


Figure 4

Figure 4 illustrates the action in Figure 3 in greater detail. If we ignore the P-type emitter region in Figure 3, the circuit of Figure 4A results. V_S makes the P-type collector region negative with respect to the N-type base region. This, of course, reverse biases the collector junction. To examine the bias on the emitter junction, we ignore the P-type collector region, as shown in Figure 4B. V_S makes the P-type emitter region positive with respect to the N-type base, thus forward biasing the emitter junction. Thus, V_S in Figure 3 has the effect of reverse biasing the collector junction and forward biasing the emitter junction. As long as one junction is reverse biased, very little current flows through the transistor. Reversing V_S only reverses the bias on the two junctions. The collector junction would be forward biased while the emitter junction would be reverse biased.

To produce a current within the transistor, an additional voltage source must be applied to the base region, as shown in Figure 5. The battery or voltage source connected to the base and emitter regions is labeled V_{BB} and the voltage source connected to the collector and emitter is labeled V_{CC}.

Let's first examine the action produced by the connection of V_{BB}. With V_{BB} connected as shown, the N-type base region is made negative with respect to the P-type emitter region. This forward biases the emitter junction. As a result, holes in the emitter region combine with electrons in the base region. The result is that BASE CURRENT (electron flow) occurs in the external circuit, as shown by the I_B arrow.

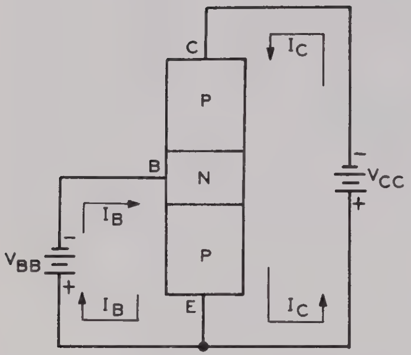


Figure 5

Figure 6 shows the action at the emitter junction in detail. To obtain the desired action in a transistor, the base region is made extremely thin. With the emitter junction forward biased, holes from the emitter region actually flow part way into the base region before recombining with the electrons in the base region. Referring back to Figure 5, note that the P-type collector region is negative with respect to the emitter. The negative potential on the collector region attracts the holes that flow into the base region. As a result, some holes flow through the base region into the collector region.

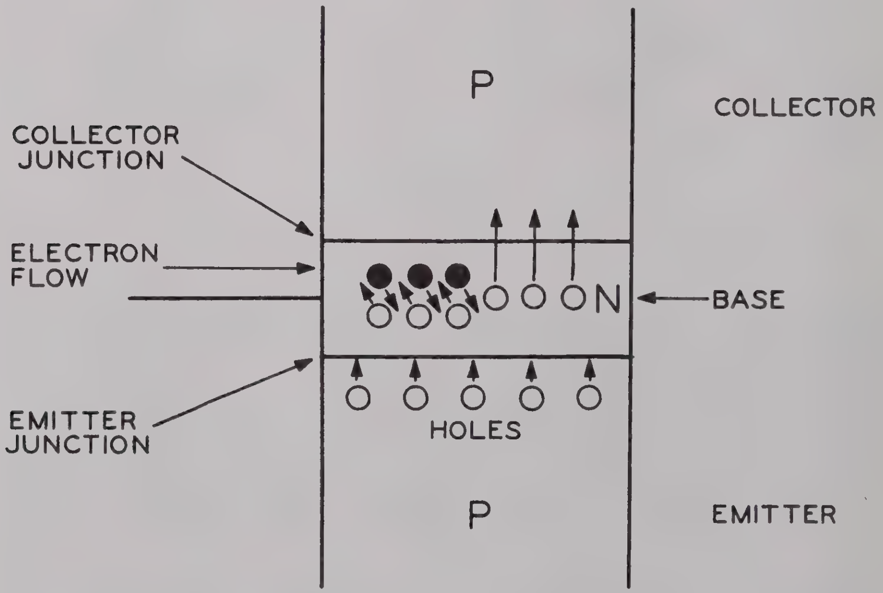


Figure 6

Holes do not flow in the external circuit. When they reach the point where the connecting wire attaches to the P material, they combine with electrons from the external circuit. The net result of the action in the base circuit is a flow of electrons in the external collector-emitter circuit, as shown by the I_C arrow in Figure 5. The current that flows in the collector circuit is referred to as COLLECTOR CURRENT, I_C.

The value of the collector current, I_C, is almost directly proportional to the value of base current I_B. Increasing the forward bias on the emitter junction (increasing the value of V_{BB}) causes more holes to flow into the base region, and thus more holes are available to flow into the collector region, thereby increasing collector current. Decreasing the value of V_{BB} produces the opposite effect.

The key to the operation of the transistor is the thinness of the base region. If the base region were too thick, the holes from the emitter region would not be able to pass through the base region into the collector region. They would recombine with electrons before reaching the collector region. The holes injected into the N-type base region are minority carriers. Thus, bipolar junction transistor operation is based on **MINORITY CARRIER INJECTION**.

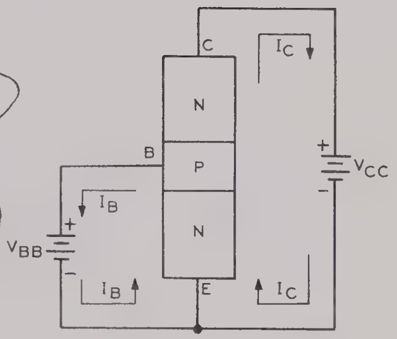
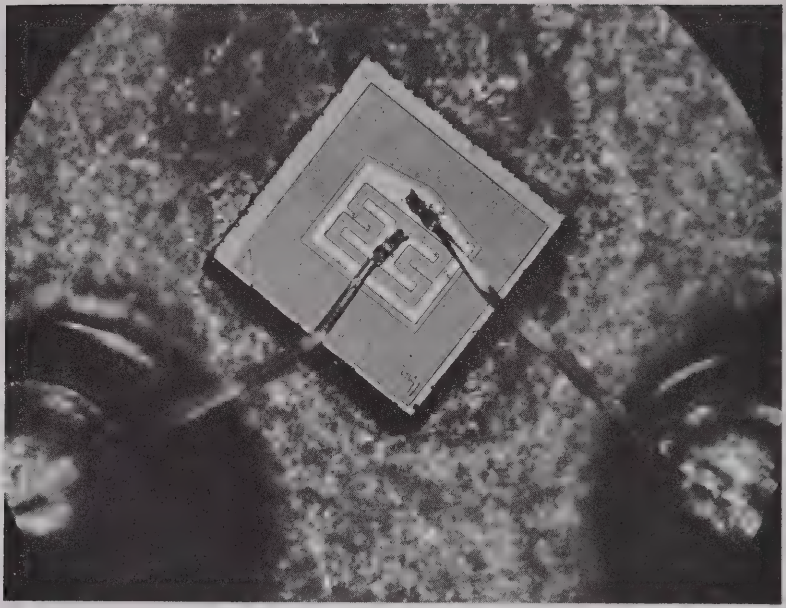


Figure 7

The circuit of Figure 5 shows a transistor constructed of a PNP sandwich of semiconductor material. A bipolar junction transistor may also be constructed in an NPN arrangement, as shown in Figure 7. The major difference between the two arrangements is the polarity of V_{BB} and V_{CC}. Remember that the emitter junction must be forward biased. In the NPN arrangement, the P-type base must be positive with respect to the emitter. This causes electrons to be injected into the P-type base region. By also making the collector region positive, the injected electrons pass through the base region into the collector region. As a result, base current I_B and collector current I_C flow in the directions shown. As in the PNP arrangement, varying V_{BB} causes I_B to change, and in turn, I_C changes. Increasing I_B increases I_C, and vice versa.

To obtain the proper transistor operation, the transistor must be biased as shown in Figures 5 and 7. Note that in both cases the emitter junction is forward biased and the collector junction is reverse biased. If the bias on either junction is reversed, proper transistor action will not occur. Thus, to obtain the proper transistor operation (base current controlling collector current), the following bias conditions are necessary:

THE EMITTER JUNCTION MUST BE FORWARD BIASED; THE COLLECTOR JUNCTION MUST BE REVERSE BIASED.



The photomicrograph above shows the construction of a typical junction transistor. The square piece of material is the transistor. Connecting leads are shown attached to the base and emitter regions. The collector connection is made through the case on which the transistor is mounted.

Courtesy Fairchild Semiconductor

In summary, we can say that the transistor is basically a current control device. The value of base current controls collector current. That is, the transistor is an "electronically controlled variable resistor."

TRANSISTOR CHARACTERISTICS

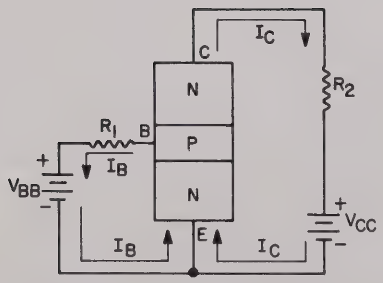


Figure 8

In a practical transistor circuit, resistance is placed in series with the base and collector supplies, to limit current to a safe value. Figure 8 shows the NPN arrangement, with the addition of current-limiting resistors. R_1 limits base current and R_2 limits collector current. Since V_{BB} forward biases the emitter junction, only a small voltage is required to produce an appreciable base current. Because the base region is very thin, excessive base current can destroy the transistor. Typical base currents range from a few microamperes to several milliamperes. The collector supply, V_{CC}, on the other hand, ~~is larger in value. This is~~ necessary because the collector must attract the carriers that are injected into the base region. Typical collector currents range from fractions of milliamperes to amperes. Thus, the collector current is always larger than the base current. As a result, the transistor can operate as an AMPLIFYING DEVICE.

As shown in Figure 8, both the base and collector currents flow in the emitter region. This action is detailed in Figure 9. Collector current I_C is shown as a heavier line to indicate that it is greater in value than base current I_B. The two currents (I_B and I_C) combine in the emitter region to form the EMITTER CURRENT, I_E.

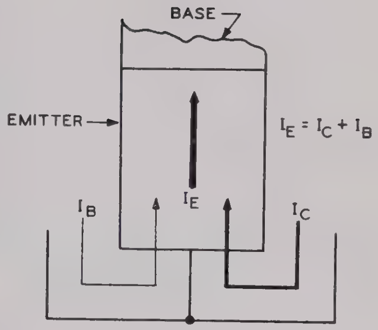


Figure 9

Schematic symbols are used to represent the PNP and NPN transistors rather than the arrangement shown in Figures 5 and 7. Figure 10A shows the symbol for the PNP transistor and Figure 10B shows the symbol for the NPN transistor. The only difference between the two is the direction of the arrow on the emitter leads.

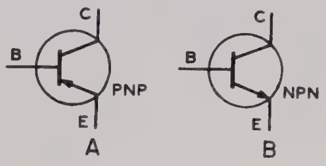


Figure 10

There are many ways in which transistors can be classified. The most basic classifications, however, can be made according to the amount of current the transistor can safely handle. The current carried by the transistor in turn determines the power dissipated by the transistors. With current or power as a basis, transistors can be classified as LOW POWER or HIGH POWER. The low-power transistors are the types commonly found in equipment such as pocket transistor radios. The signal levels found in such devices are very small. The low-power transistors are also called SMALL-SIGNAL transistors.

High-power high-fidelity stereo amplifiers and many industrial devices employ high-power transistors. High-power transistors are also referred to as LARGE-SIGNAL transistors, since the signal levels found in the equipment are quite high.

When analyzing transistor circuits, it is convenient to consider the voltages which appear between the three terminals of a transistor. Figure 11 shows a common method of identifying these voltages. The voltage from the collector to the emitter is called COLLECTOR-TO-EMITTER voltage and is indicated as V_{CE}. Likewise, the BASE-TO-EMITTER voltage is indicated as V_{BE} and the COLLECTOR-TO-BASE voltage is indicated as V_{CB}.

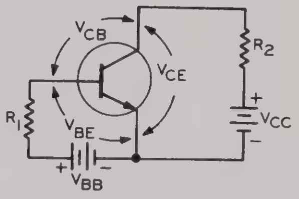


Figure 11

V_{CB} is actually the voltage across the collector junction and V_{BE} is the voltage across the emitter junction. As mentioned earlier, the emitter junction is normally forward biased, and the collector junction is reverse biased. With the emitter junction forward biased, it has a very low resistance and a very low voltage drop. Typical values of V_{BE} are between .2 and .3 volt for germanium transistors and between .6 and .7 volt for silicon transistors. With the collector junction reverse biased, it represents a high resistance, and as a result, V_{CB} is quite high. The collector-to-emitter voltage, V_{CE}, is equal to the sum of V_{CB} and V_{BE}. In a typical circuit, V_{CE} is somewhat less than V_{CC}. (Actually, V_{CE} equals V_{CC} minus the voltage drop across R_2.) For example, a circuit in a transistor radio receiver employing a 9-volt supply may have a V_{CE} of 5 volts.

To analyze the operation of a transistor in a circuit, it is necessary to know exactly how collector current I_C varies with changes in base current I_B and the other electrode voltages. This information is generally given in the form of a graph or **CHARACTERISTIC CURVE.** Manufacturers usually supply these characteristic curves for the various transistors they manufacture.

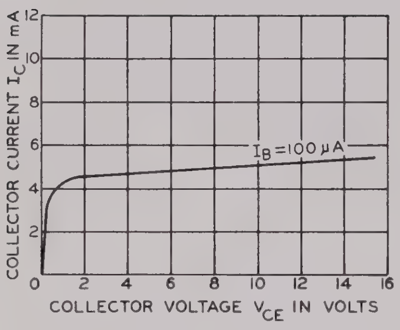


Figure 12

Figure 12 shows a characteristic curve for a typical small-signal transistor. This curve shows how collector current varies as the collector-to-emitter voltage, V_{CE}, is varied from 0 to 16 volts. The base current, I_B, is fixed at 100 μA. A great deal of information can be obtained from such a curve.

Suppose that you want to know how much collector current is produced when V_{CE} is equal to 10 volts and $I_B = 100\ \mu A$. Start with the V_{CE} scale at the bottom of the graph, and locate the value 10. From this point, move up the vertical line to the curve. Then move horizontally from this point to the I_C scale at the left of the graph. This brings you to a point between 4 and 6 mA, about 5.2 mA. Therefore, the collector current is 5.2 mA when V_{CE} is 10 volts and I_B is 100 μA.

As a second example, a collector-to-emitter voltage of 14 volts brings you to a point a little higher on the I_C scale, about 5.4 mA. Thus, with V_{CE} equal to 14 volts, I_C is equal to 5.4 mA.

Note that, as V_{CE} is increased from 0 to 2 volts, I_C increases from 0 to about 4.5 mA. However, increasing V_{CE} above 2 volts produces very little change in I_C. At 15 volts I_C rises to about 5.5 mA. This curve shows us that, beyond a certain V_{CE}, I_C is relatively independent of changes in V_{CE}. The transistor is therefore considered to be a **CONSTANT CURRENT DEVICE** regarding the effect of V_{CE} on I_C.

The curve of Figure 12 shows the characteristics of the transistor for a given value of base current. However, as explained earlier, collector current varies approximately in direct proportion to base current. If base current is increased in Figure 12, the line would be higher on the graph, indicating a higher value of collector current. Likewise. if base current is decreased, the line would be lower on the graph.

To more completely represent the characteristics of the transistor, lines representing several values of base current are drawn on the same graph, as shown in Figure 13. This arrangement is referred to as a **FAMILY OF CHARACTERISTIC CURVES**. The curves of Figure 13 show exactly how the collector current varies with changes in base current at a given value of collector-to-emitter voltage. For example, suppose that V_{CE} is 8 volts. When I_B is 50 μA, I_C is 2 mA (point A). Increasing I_B to 100 μA increases I_C to 5 mA (point B). With I_B at 200 μA, I_C is 10 mA (point C.) Thus, the family of characteristic curves provides a means of predicting the collector current for various values of base current. This enables us to examine the operation of transistor circuits in a quick, simple manner.

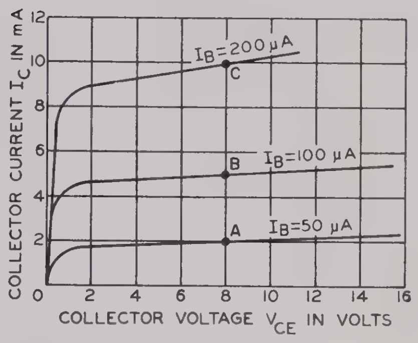


Figure 13

A tape recorder employs many transistor amplifier circuits. As in most units, the common-emitter configuration is the most common.
Courtesy Bell and Howell

TRANSISTORS AS AMPLIFIERS

One of the main functions of a device such as a transistor is to operate as an **AMPLIFIER**. Most circuits found in electronic equipment are basically amplifiers. An amplifier is a circuit that increases the level of a **SIGNAL**. The term signal refers to a voltage or current that exists in a circuit. For example, in a radio receiver, the energy that travels through space induces a very small voltage into the radio receiver's antenna. Before this signal can be processed and applied to the speaker, its amplitude must be increased. Several amplifier circuits perform this task in the receiver.

Amplifier Action

Let's examine briefly how a transistor can be used to form an amplifier circuit. Figure 14 shows a simple transistor amplifier circuit. The transistor is labeled as Q_1. The Q designation for a transistor is widely accepted. E_{IN} represents the input signal to this circuit. R_1 limits base current to the desired value. The resistance, R_L, in the collector circuit is the **LOAD RESISTOR**. The purpose of this resistance is to develop the output signal, E_O. Collector current I_C, flowing through R_L, develops a voltage drop of the indicated polarity.

To examine the operation of the circuit, suppose that E_{IN} is zero. Under these conditions, no forward bias is applied to the emitter junction. Thus, I_B is zero. Collector current is directly proportional to base current, so that when $I_B = 0$, $I_C = 0$. With $I_C = 0$, no voltage is developed across R_L, and E_O is zero.

However, when E_{IN} is increased, I_B increases. In turn, I_C increases, developing a voltage drop, E_O, across R_L. Further increases in E_{IN} cause increases in I_B, I_C and E_O. By choosing the values of R_1, R_L and V_{CC} correctly, E_O can be made many times larger than E_{IN}. This action is referred to as VOLTAGE AMPLIFICATION.

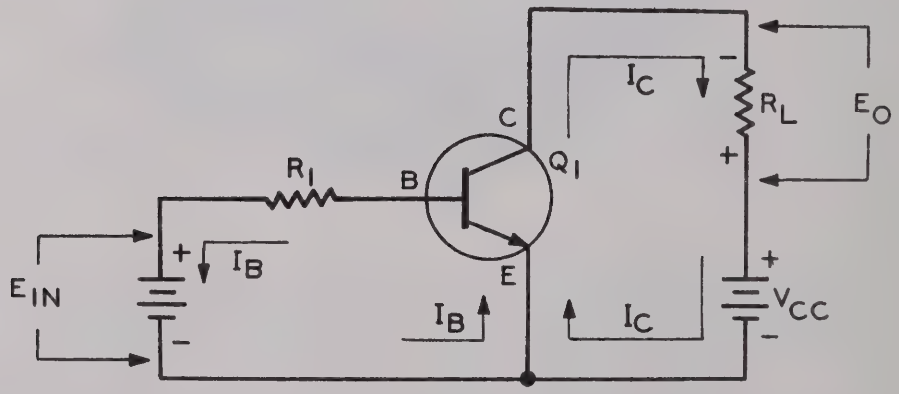


Figure 14

The previous discussion shows how the transistor serves as a voltage amplifier. The transistor can also be thought of as a **CURRENT AMPLIFIER**. In this case, the input signal would be the base current while the output signal is the collector current. The amplification occurs since a given value of base current develops a given value of collector current. Referring back to Figure 13, a base current of 50 μA with V_{CE} equal to 8 volts produces

The following Practice Exercise questions cover the subjects which you have just studied. They are:

BASIC TRANSISTOR OPERATION

TRANSISTOR CHARACTERISTICS

1. What action prevents further recombination in a PN junction diode?
2. What are majority carriers and minority carriers?
3. A bipolar junction transistor has (a) one PN junction, (b) two PN junctions, (c) three PN junctions.
4. What are the names given to the three semiconductor regions in a transistor?
5. In the circuit of Figure 5, V_{BB} provides the emitter junction with (a) forward bias, (b) reverse bias.
6. The holes which flow into the N-type base region in Figure 6 would be referred to as (a) majority carriers, (b) minority carriers.
7. What happens to I_C in Figure 5 if I_B is decreased?
8. Transistors operate by ____________________ carrier injection.
9. What is the main difference between the circuits for NPN and PNP transistors?
10. What are the proper bias conditions for a transistor?

11. In a transistor, the base current is generally greater than the collector current. True or False?

12. What is emitter current equal to in a transistor?

13. Draw a circuit like that of Figure 8 for a PNP transistor using the PNP transistor schematic symbol. Be sure to observe the correct polarity of V_{BB} and V_{CC}.

14. Explain the difference between small- and large-signal transistors.

15. In a transistor circuit, you would normally expect V_{BE} to be (a) larger than V_{CB}, (b) smaller than V_{CB}.

16. What range of V_{BE} would you expect if the emitter junction of a germanium transistor is forward biased?

17. Using the characteristic curve of Figure 12, what value of I_C results when V_{CE} is 4 volts?

18. With the information presented in Figure 12, we can say that the transistor is a constant ____________________ device.

19. What is the name given to the characteristic curves of Figure 13?

20. Referring to Figure 13, suppose that V_{CE} is 10 volts. What is the CHANGE in I_C if I_B is increased from 50 to 100 μA?

a collector current of 2 mA. Thus, the collector current is many times larger than the base current, in this case 40 times larger.

There is often some confusion about the operation of an amplifier. The input signal is not actually amplified or made large. Instead, the input signal is used to control the conduction of the transistor. In turn, the transistor determines how much energy is taken from the power supply and applied to the load. The amplifier circuit is therefore a CONTROL DEVICE. The amplifier merely controls the energy delivered to the load from the power supply.

Transistor Amplifier Types

The basic transistor amplifier circuit of Figure 14 may be represented by the block diagram of Figure 15. G represents the input signal, voltage or current variation, Q is the transistor and L represents the load. Notice that one lead of the signal source G connects to the input electrode of the transistor while the load connects to the output electrode. The other leads of the load and signal source connect to the third electrode of the transistor. In other words, one electrode of the transistor is common to both the input and output circuits. By properly arranging the circuit, any one of the transistor electrodes can be made the common electrode.

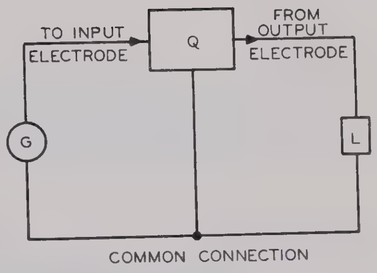


Figure 15

Taking the circuit of Figure 14 and applying the arrangement of Figure 15 produces the circuit of Figure 16. Since the emitter in this circuit is common to both input and output circuits, the arrangement is called a **COMMON-EMITTER AMPLIFIER**.

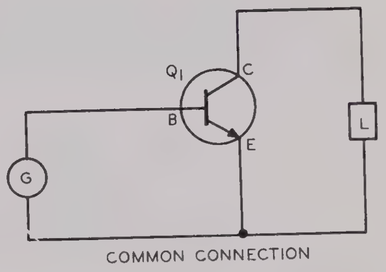


Figure 16

If the base electrode is connected as the common electrode, the circuit of Figure 17 results. This type of circuit is referred to as a **COMMON-BASE AMPLIFIER**. Even though the emitter is considered as the input electrode, the input signal still causes variations of base current. Variations in base current cause collector current to vary and an output signal to be developed across the load.

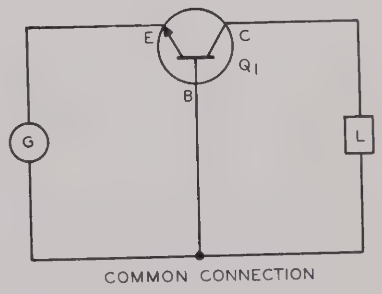


Figure 17

When the collector is arranged as the common electrode, the **COMMON-COLLECTOR AMPLIFIER** of Figure 18 results. In this circuit the load carries not only the collector current but the base current as well, since $I_E = I_C + I_B$.

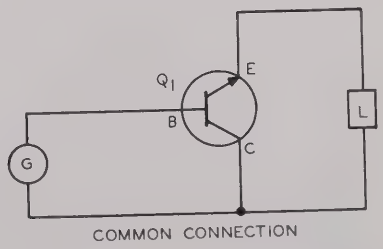


Figure 18

Each of the amplifier circuit arrangements has advantages and disadvantages. Of the three arrangements, the common-emitter configuration is the most widely used. The other two configurations, however, find use in special applications.

TRANSISTOR CONSTRUCTION

A transistor is composed of two parts: the semiconductor material and the can or package.

Chip Fabrication

The piece of semiconductor material (sometimes called a chip) which makes up a bipolar junction transistor is quite small, usually less than 1/10 inch square for small-signal transistors. A power, or large-signal transistor, employs a larger piece of semiconductor material, as the current and resultant power dissipation are higher.

As shown earlier, the transistor is basically a sandwich of P-type and N-type semiconductor materials. To obtain the desired transistor action, the semiconductor material must be formed in the correct manner. The N-type and P-type materials are just not "glued together." Instead, transistors are fabricated by one or more of the three processes: alloying, growing and diffusing.

There are many transistor manufacturing techniques. Quite often, transistors are named or classified according to the particular manufacturing technique employed. One of the earliest arrangements was the ALLOY JUNCTION transistor pictured in Figure 19. In the alloy junction transistor, two "dots" of N-type semiconductor material are placed on opposite sides of a thin wafer of P-type material. The assembly is heated until the

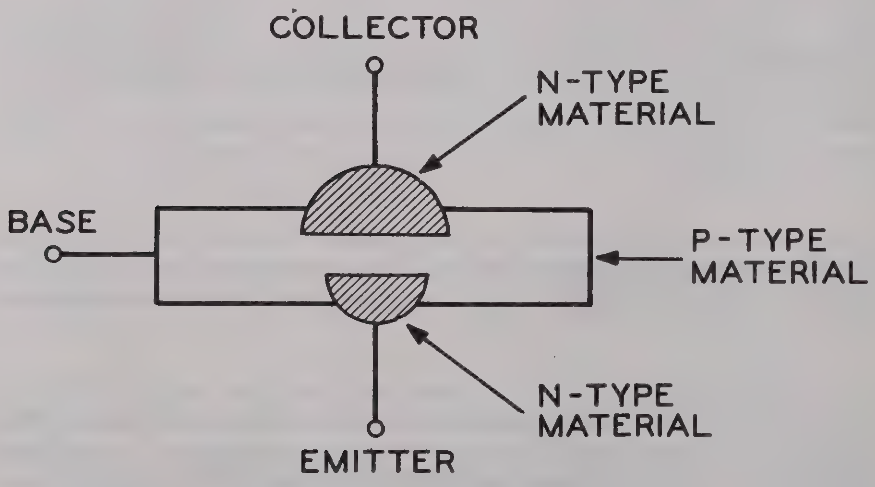


Figure 19

"dots" alloy with the wafer to form the emitter and collector regions. A PNP transistor would be made by alloying P-type dots with an N-type wafer.

The GROWN JUNCTION transistor closely resembles the structure pictured earlier in Figure 2. To produce this type of transistor, the impurities are changed while the semiconductor material is made, or "grown," so that alternate N and P layers are formed.

Figure 20 shows the structure of a DIFFUSED PLANAR transistor. The transistor starts out as a wafer of N-type material, as shown in Figure 20A. By subjecting the wafer to high temperatures and a gas that acts as an acceptor, a P-type layer for the base is diffused into the N-type material, as shown in Figure 20B. The gas is then changed to a type which acts like a donor, and an N-type emitter layer is diffused into the P-type base material. The transistor shown in Figure 20C is manufactured so that the edges of the two junctions are on the top surface of the wafer. Connections are then made to the three regions to provide the collector, base and emitter connections. A PNP transistor can be formed in a similar manner. A MESA transistor is formed if the sides of the wafer are etched away with acid, as shown in Figure 20D.

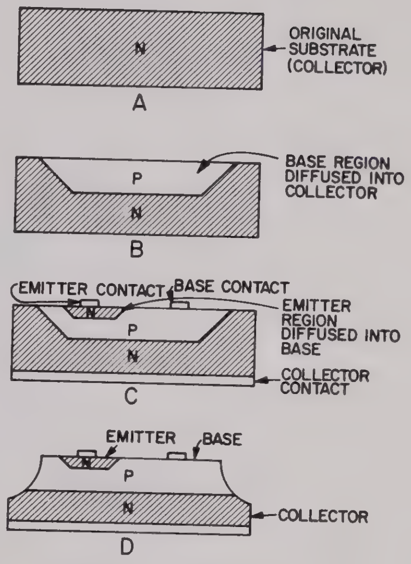

N
ORIGINAL SUBSTRATE (COLLECTOR)
A
P
N
BASE REGION DIFFUSED INTO COLLECTOR
B
EMITTER CONTACT
BASE CONTACT
N
P
N
EMITTER REGION DIFFUSED INTO BASE
COLLECTOR CONTACT
C
EMITTER
BASE
N
P
N
COLLECTOR
D

Figure 20

The EPITAXIAL transistor is similar to the diffused type shown in Figure 20. The difference is that the collector region is grown on a piece of semiconductor material. The base and emitter regions are then diffused into the collector region.

When the majority of transistors being manufactured were germanium, many or most were of the alloy type. Later, many germanium transistors were processed by the mesa diffusion method. Mesa transistors lend themselves to very high frequency applications. Most of the germanium transistors are PNP.

Some early silicon transistors were of the grown junction type, but most recent ones are made by the diffusion technique, thus permitting the manufacture of planar and mesa transistors. Most silicon transistors are basically of these two kinds, with NPN types the most common. Most transistors that are presently produced are the silicon types.

There are many other ways to fabricate transistors. Each way has advantages and disadvantages. Some transistors are fabricated for high-frequency applications, whereas others are fabricated for low-frequency or power applications. Modern integrated circuits are fabricated around the diffusion

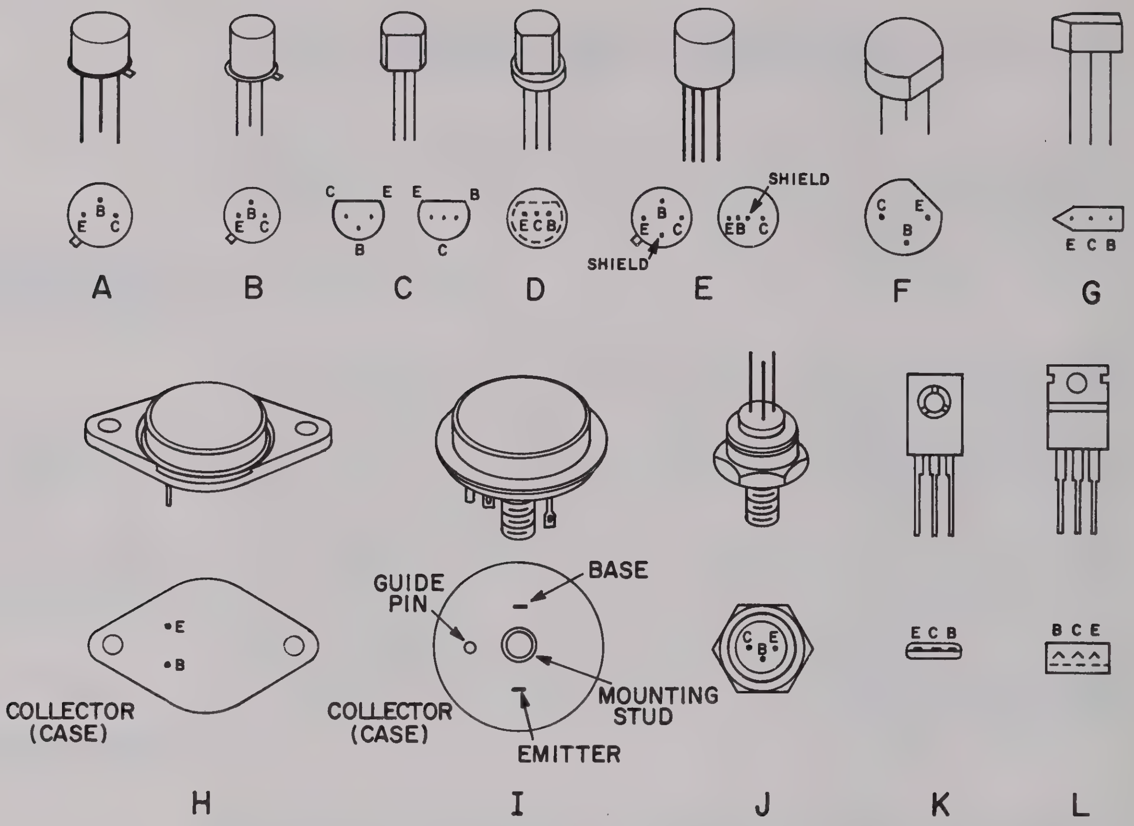


Figure 21

technique shown in Figure 20. Resistors, capacitors and other components can be formed in a single piece of semiconductor material using this technique. Complete circuits can be manufactured in this manner at low cost.

Case Styles

To protect the transistor, as well as provide a means of attaching connecting leads, the transistor is mounted in a case (sometimes called "package"). Figure 21 shows several of the more common case styles, approximately full size. Cases A to G are generally employed for small-signal transistors. A metal container is generally employed for cases A, B and E. This affords some shielding, as well as providing a hermetic seal. On some transistors of this type, the connection to the collector also connects to the case. When working on circuits with transistors of this type, care should be exercised so that shorts between the transistor case and nearby components do not occur.

Many of the transistors used today are encapsulated into molded epoxy or plastic cases. Cases C, D, F and G are common styles for epoxy and plastic transistors. This type of case is adequate for most normal applications, such as in radios, TV receivers and many industrial applications. Where high reliability is required, the metal case arrangements discussed previously are employed.

Large-signal or power transistors are designed to carry a larger collector current, and they therefore must dissipate more power. To accomplish this, the semiconductor material, as well as the case, is made larger. In Figure 21, cases H to L are common power transistor cases. Cases H, I and J are made of metal, while cases K and L are made of plastic. All five power transistors (H through L) should be mounted on heat sinks to effectively dissipate the heat produced. Generally, the collector is connected to the case in a power transistor. This is an electrical, as well as a mechanical connection, so that good heat transfer from the resistor itself occurs.

HEAT SINKS

Because heat affects operation and can even damage a transistor, it is important to keep a transistor cool. One of the most common methods of cooling a transistor is to mount it on something that will carry heat away from the transistor. A transistor can sometimes be mounted to the chassis. Heat is then given from the transistor to the chassis. Both the chassis and the transistor radiate heat into the air. In this way the transistor is kept cooler.

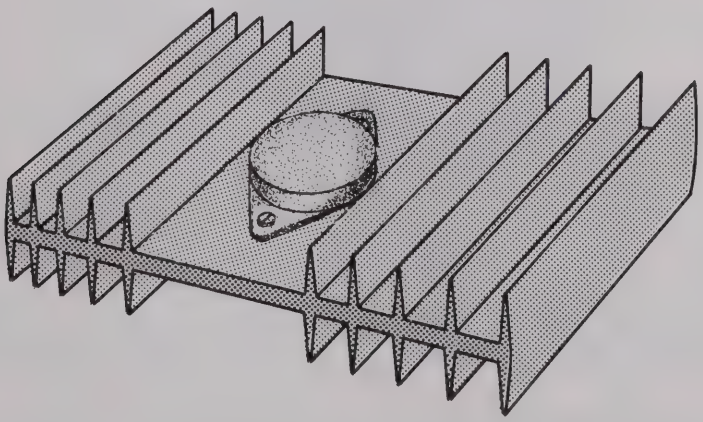
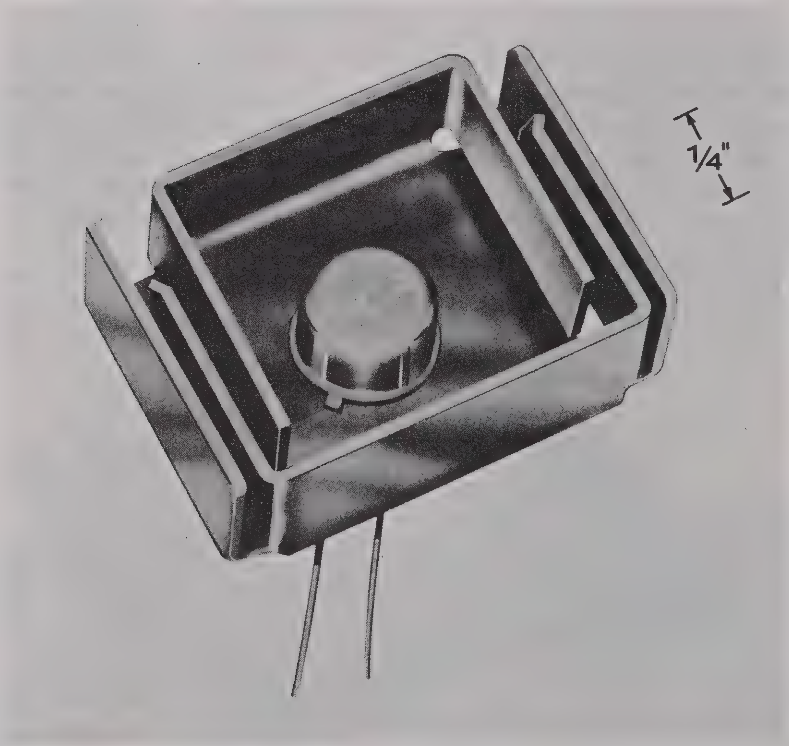


Figure 22

A device designed to take heat from a transistor and radiate it into the air or some other surrounding material is called a HEAT SINK. Instead of mounting the transistor to the chassis, the transistor can be mounted on a separate heat sink. A typical heat sink with a power transistor mounted on it is shown in Figure 22. Note its finned design, which provides a large surface area in a relatively small space, and allows a large amount of heat to be radiated into the air. Various styles of heat sinks are used, but all provide a large surface area to transfer a maximum amount of heat to the surrounding air. Heat sinks are usually made of aluminum because it conducts heat easily.

Generally, the collector of a power transistor is connected to the case. This is an electrical as well as a mechanical connection. When the collector of a power transistor is connected to its case, it is often necessary to provide electrical insulation between the transistor and the heat sink. However, a good thermal connection is necessary for the heat sink to aid the transistor in dissipating its heat. A thin mica sheet is often used as the insulator, and the power transistor, insulating washer and heat sink can have a heat-conducting SILICONE GREASE applied to their mating surfaces as a further aid to heat dissipation.



The heat sink on the transistor shown above helps to dissipate the heat and allow the transistor to operate at a higher power level.

Courtesy RCA Electronic Components

TRANSISTOR TESTING

In general, transistors suffer less failures than vacuum tubes. The main reason for this is that they have no filaments (the main cause of vacuum tube failure). Transistors, however, can become defective. This is often a result of excessive current, temperature or both. There are many elaborate instruments which are available for checking the characteristics of transistors. However, some simple tests can be performed with an ohmmeter. These will indicate if the transistor is open or shorted, the most common failures. One word of caution. Some ohmmeters use a high test voltage on the high ohms ranges. Do not use the highest range. It is also not a good idea to use the lowest range either, as excessive current may be drawn.

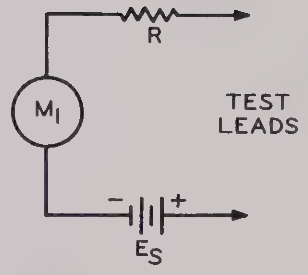


Figure 23

As shown in Figure 23, an ohmmeter is basically a current meter, M_1, in series with a voltage source, E_S, and a current-limiting resistor, R. The resistance between the points touched with the test leads determines the meter reading. The current meter scale is calibrated in ohms.

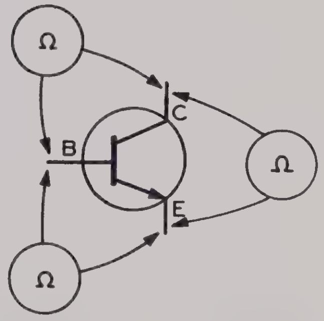


Figure 24

The ohmmeter's internal supply can be used to bias the junctions in a transistor, and the resistance may then be noted. Figure 24 illustrates the procedure. First, connect the ohmmeter to the base and emitter. Note the reading, reverse the leads and again note the reading. If the base-to-emitter junction is good, you should obtain one high reading and one low reading. If both readings are low, the junction is probably shorted. An open junction is indicated if both readings are high. The collector-to-base junction can be checked in a similar manner. Again, one reading should be high, and the other low, if the collector junction is good. Germanium transistors generally have somewhat lower function resistances than do silicon transistors.

Sometimes, transistors (especially germanium power types) develop emitter-to-collector shorts. This type of short circuit is not revealed by the base-to-emitter or collector-to-base measurements. Therefore, it is helpful to also perform an ohmmeter check between the emitter and collector. This resistance is rather low in both directions. However, it is not as low as the lower resistance measurement of either the base-to-emitter or collector-to-base junctions.

The ohmmeter can also be used to determine if a transistor is either an NPN or PNP type. First, you must know the polarity of the ohmmeter battery. The red lead is not always positive with respect to the black lead. Check the ommeter's specifications to be sure. To explain the procedure, suppose that the red lead is negative and the black lead is positive. To determine if a transistor is either an NPN or PNP type, connect the ohmmeter to the transistor's base and emitter. Reverse the leads, if necessary, to get a low resistance reading (emitter junction forward biased). Because the black lead is positive, it must be connected to the P-type material for a low reading. If the black lead is on the emitter, the transistor is a PNP type. With the black lead on the base, the transistor is an NPN type. Remember not to use either the lowest or highest ohmmeter ranges, because of the reasons that have been given.

When testing power transistors with an ohmmeter, you may get lower readings in both directions than would be obtained with small-signal transistors. This is normal for power transistors.

There are many different types of equipment available for testing and evaluating transistors. This equipment ranges from simple junction testers (such as a multimeter) to elaborate transistor "curve tracers" that show the performance characteristics of the transistor being tested.

Transistor testers provide a convenient means of testing transistors. This particular unit can test transistors without removing them from the circuit.

Courtesy Sencore Inc.

PHOTOTRANSISTORS

A **PHOTOTRANSISTOR** is a bipolar junction transistor which has a special, light-sensitive base region. A lens in the transistor case focuses light on this special base region. The light striking the lens controls the value of collector current by changing the emitter-to-collector resistance in proportion to the amount of light shining on the base region. The phototransistor symbol is shown in a simple common-emitter circuit in Figure 25.

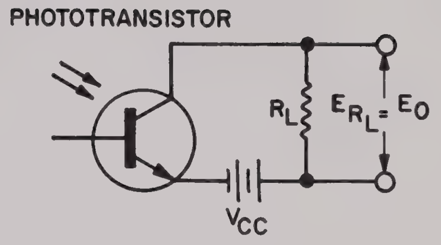


Figure 25

When it is not exposed to light, the phototransistor exhibits a high emitter-to-collector resistance, which permits only a very small collector current, and therefore, a very low output voltage, E_O. When light does strike the base material, collector current increases because of a decrease in the emitter-to-collector resistance. This also increases E_O.

In some phototransistors, an electrical connection to the base may be used for forward bias to assist the light-induced current in low-level light conditions. Most phototransistors are currently used in switching applications because of their high-speed operations. When pulsed by an LED (light-emitting diode), a typical phototransistor will switch on and off again in less than 10 μsec.

SUMMARY

The bipolar junction transistor is a three layer structure of P-type and N-type semiconductor materials. Either a PNP or an NPN arrangement can be used. The connections to the three regions are called the emitter, base and collector.

With a PNP or NPN arrangement, the transistor has two PN junctions. For proper operation, the junction between the base and emitter (the emitter junction) is forward biased, and the junction between the base and collector (the collector junction) is reverse biased.

The transistor is basically a current-control device. The base current controls the collector current. Since a very small base current controls a larger collector current, the transistor serves as an amplifier.

There are several circuit arrangements for transistor amplifiers. These are classified according to the transistor element which is common to both the input and output circuit. Since the transistor has three electrodes, there are three circuit configurations: common-emitter, common-base and common-collector. The common-emitter configuration is the most widely employed.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TRANSISTORS AS AMPLIFIERS

AMPLIFIER ACTION

TRANSISTOR AMPLIFIER TYPES

TRANSISTOR CONSTRUCTION

CHIP FABRICATION

CASE STYLES

HEAT SINKS

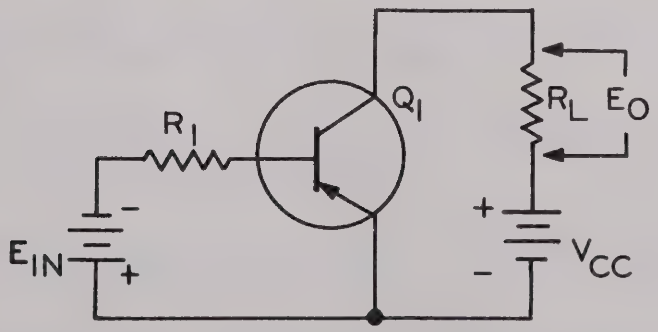
TRANSISTOR TESTING

PHOTOTRANSISTORS

21. What is the value of I_C in Figure 14 when I_B is zero?

22. How does the circuit of Figure 14 serve as an amplifier?

23. Will the circuit shown below operate as an amplifier? If not, what changes are necessary?



24. Why is an amplifier circuit really just a control device?

25. A transistor can operate only as a voltage amplifier. True or False?

26. Name the three basic transistor amplifier configurations.

27. Which amplifier configuration is most widely used?

28. What are the three basic types of transistor manufacturing processes?

29. Referring to Figure 21, the case style that would be used for a power transistor is (a) A, (b) D, (c) H.

30. What is the purpose of a heat sink?

31. How would you test a transistor with an ohmmeter?

32. Compared to small signal transistors, the junction resistances of power transistors are generally (higher) (lower).

IMPORTANT DEFINITIONS

AMPLIFIER — A circuit used to increase the level of a signal voltage or current.

BASE — One element of a transistor. In the bipolar junction transistor, the base is the center section.

BIPOLAR JUNCTION TRANSISTOR — The most common form of a transistor, having two PN junctions and available in both NPN or PNP types. The bipolar junction transistor can be constructed of either silicon or germanium material.

CHARACTERISTIC CURVE — A graph showing the relationship between electrode voltages and currents in a transistor.

COLLECTOR — One element of a transistor. In the bipolar junction transistor the collector is one end section.

COLLECTOR JUNCTION — The PN junction between the base and collector regions in a transistor. Also called the collector-base junction.

COMMON-BASE AMPLIFIER — A transistor amplifier circuit in which the base is common to both the input and output circuits.

COMMON-COLLECTOR AMPLIFIER — A transistor amplifier circuit in which the collector is common to both the input and output circuits.

COMMON-EMITTER AMPLIFIER — A transistor amplifier circuit in which the emitter is common to both the input and output circuits.

CONSTANT CURRENT DEVICE — A device such as a transistor in which current is relatively independent of voltage.

CURRENT AMPLIFIER — An amplifier circuit which develops an output current larger than the input current.

EMITTER — One element of a transistor. In the bipolar junction transistor, the emitter is one end section.

EMITTER JUNCTION — The PN junction between the base and emitter regions in a transistor. Also called the emitter-base junction.

IMPORTANT DEFINITIONS (Continued)

FAMILY OF CHARACTERISTIC CURVES — A graph including several general characteristic curves for a particular transistor. As an example, a family of collector characteristic curves includes curves for different values of base current.

LOAD RESISTOR — A resistor in a transistor output circuit used to develop the output signal.

MAJORITY CARRIERS — The current carriers (holes or electrons) present in the greater numbers. In N-type material the majority carriers are electrons and in P-type material the majority carriers are holes.

MINORITY CARRIERS — The current carriers (holes or electrons) present in fewer numbers. In N-type material the minority carriers are holes and in P-type material the minority carriers are electrons.

MINORITY CARRIER INJECTION — The basic bipolar junction transistor action where minority carriers are injected into the base region and pass through the base region to be collected by the collector region.

PHOTOTRANSISTOR — A bipolar junction transistor whose base resistance decreases when light strikes the base. The case for this transistor contains a lens that focuses light on the base region.

SIGNAL — A voltage or current that represents some information.

TRANSISTOR — A semiconductor device with three or more electrodes.

ESSENTIAL SYMBOLS AND EQUATIONS

V_{CE}	Collector-to-emitter voltage
V_{BE}	Base-to-emitter voltage
V_{CB}	Collector-to-base voltage
I_C	Collector current
I_B	Base current
I_E	Emitter current
V_{BB}	Base supply voltage
V_{CC}	Collector supply voltage

PRACTICE EXERCISE SOLUTIONS

1. **The recombination at the PN junction sets up a potential hill or barrier which prevents further recombination.**

2. **Majority carriers are holes in P-type material and electrons in N-type material. Minority carriers are holes in N-type material and electrons in P-type material.**

3. **(b) two PN junctions. — They are the emitter junction and the collector junction.**

4. **Base, emitter and collector.**

5. **(a) forward bias. — When the N-type region is made negative with respect to the P-type region, the junction is forward biased.**

6. **(b) minority carriers. — In N-type material, holes are minority carriers and electrons are majority carriers.**

7. **I_C decreases. — I_B decreases when V_{BB} is decreased. Decreasing I_B reduces the number of holes injected into the base region.**

8. **minority**

9. **The supply voltage polarities, as well as the directions of current flow, are opposite in the NPN and PNP circuits.**

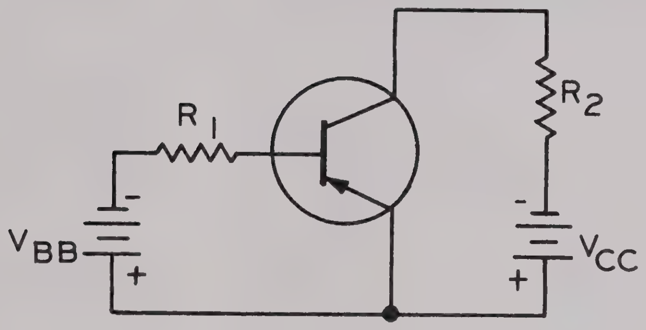
10. **The emitter junction must be forward biased and the collector junction must be reverse biased.**

11. **False — Collector current is greater than base current under normal operating conditions.**

12. **Emitter current is equal to the sum of base and collector currents, $I_E = I_B + I_C$.**

PRACTICE EXERCISE SOLUTIONS (Continued)

13.



14. Small-signal transistors are used in low-power applications, whereas large-signal transistors are used in high-power applications.

15. (b) smaller than V_{CB}. — V_{BE} is generally smaller than V_{CB} in a normally biased circuit.

16. V_{BE} for a germanium transistor would generally be between .2 and .3 volt with the emitter junction forward biased. For a silicon transistor V_{BE} would be between .6 and .7 volt.

17. Slightly less than 5 mA.

18. current — Beyond a given value of V_{CB}, I_C remains relatively constant with changes in V_{CE}.

19. They are called a family of characteristic curves.

20. 3 mA. — When $I_B = 50\ \mu A$, $I_C = 2$ mA; and when $I_B = 100\ \mu A$, $I_C = 5$ mA. Thus, I_C increases from 2 mA to 5 mA, for a change of 3 mA, when I_B increases from 50 μA to 100 μA.

21. Zero. — Since I_C is directly proportional to I_B, when $I_B = 0$, $I_C = 0$.

22. Changes in E_{IN} cause changes in I_B. In turn, the changes in I_B vary I_C, which develops the output voltage, E_O, across R_L. Generally, the output signal E_O is larger than the input signal E_{IN}.

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ONE OF THE
BELL & HOWELL SCHOOLS

1043A
EXAMINATION CHECK SHEET

1043A

1. D - RECOMBINATION AT A PN JUNCTION -- MAKES THE N MATERIAL POSITIVE.
At the PN junction, holes combine with electrons -- leaving the N material with a positive charge and the P material with a negative charge.

2. C - A TRANSISTOR HAS -- TWO PN JUNCTIONS.
The two PN junctions in a transistor are referred to as the emitter junction and the collector junction.

3. A - IN A TRANSISTOR, -- COLLECTOR CURRENT IS ALMOST DIRECTLY PROPORTIONAL TO BASE CURRENT.
The base current in a transistor controls the collector current. Increasing base current increases collector current, and decreasing base current decreases collector current.

4. D - THE MAIN DIFFERENCE BETWEEN NPN AND PNP TRANSISTOR CIRCUITS IS -- SUPPLY VOLTAGE POLARITY.
The basic operation of NPN and PNP transistors is the same. Both types employ minority carrier injection; the major difference is the polarity of the supply voltages.

5. C - FOR NORMAL OPERATION, A TRANSISTOR IS BIASED SO THAT -- THE COLLECTOR JUNCTION IS REVERSE BIASED AND THE EMITTER JUNCTION IS FORWARD BIASED.
Minority carrier injection and correct transistor operation depend upon a forward biased emitter junction and a reverse biased collector junction.

6. B - IN THE SCHEMATIC SYMBOL FOR AN NPN TRANSISTOR, -- THE ARROW ON THE EMITTER LEAD POINTS AWAY FROM THE BAR.
The emitter lead arrow points toward the bar in the schematic symbol for a PNP transistor.

7. B - WITH RESPECT TO THE RELATIONSHIP BETWEEN V_{CE} AND I_C, -- I_C IS CONSTANT BEYOND A CERTAIN VALUE OF V_{CE}.
The transistor is a constant current device. Beyond a certain value of V_{CE}, I_C remains relatively constant.

8. C - THE OUTPUT SIGNAL IN A TRANSISTOR AMPLIFIER -- IS DEVELOPED BY COLLECTOR CURRENT IN THE COLLECTOR LOAD RESISTOR.
Collector current flowing through the collector load resistor develops the output signal. In most circuits, the output signal is higher than the input signal.

9. A - THE MOST COMMON TRANSISTOR AMPLIFIER CONFIGURATION IS THE -- COMMON EMITTER.
Although the other types are used, this circuit provides the highest gain and is the most widely used.

10. A - ASSUME THAT THE CIRCUIT OF FIGURE 14 IS OPERATING PROPERLY. IF A SHORT IS PLACED FROM BASE TO EMITTER ON Q_1, COLLECTOR CURRENT WILL -- DROP TO NEAR ZERO.
With a base-emitter short, there is no forward bias on the emitter junction and collector current will drop to near zero.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1043A

Example:

A ☐ B ☐ C ■ D ☐

An eagle is a type of

A. fish. B. tree. C. bird. D. dog.

1. A ☐ B ☐ C ☐ D ☒
Recombination at a PN junction
(A) makes the N material negative. (B) makes the P material positive. (C) makes the junction neutral. (D) makes the N material positive.

2. A ☐ B ☐ C ☒ D ☐
A bipolar junction transistor has
(A) four PN junctions. (B) three PN junctions. (C) two PN junctions. (D) one PN junction.

3. A ☒ B ☐ C ☐ D ☐
In a transistor,
(A) collector current is proportional to base current. (B) collector current is inversely proportional to base current. (C) collector current is less than base current. (D) base current is greater than emitter current.

4. A ☐ B ☐ C ☐ D ☒
The main difference between NPN and PNP transistor circuits is
(A) majority carrier injection in NPN transistors and minority carrier injection in PNP transistors. (B) minority carrier injection in NPN transistors and majority carrier injection in PNP transistors. (C) collector current is higher in the NPN type. (D) supply voltage polarity.

5. A ☐ B ☐ C ☒ D ☐
For normal operation, a transistor is biased so that
(A) both collector and emitter junctions are forward biased. (B) both collector and emitter junctions are reverse biased. (C) the collector junction is reverse biased and the emitter junction is forward biased. (D) the collector junction is forward biased and the emitter junction is reverse biased.

6. A ☐ B ☒ C ☐ D ☐
In the schematic symbol for an NPN transistor,
(A) the arrow on the emitter lead points toward the bar. (B) the arrow on the emitter lead points away from the bar. (C) the collector lead arrow points toward the bar. (D) the collector lead arrow points away from the bar.

7. A ☐ B ☒ C ☐ D ☐
With respect to the relationship between V_{CE} and I_C,
(A) I_C is directly proportional to all values of V_{CE}. (B) I_C is relatively constant beyond a certain value of V_{CE}. (C) I_C decreases as V_{CE} increases. (D) V_{CE} decreases as I_C increases.

8. A ☐ B ☐ C ☒ D ☐
The output signal in a transistor amplifier
(A) is a result of base current in the collector load resistor. (B) is always less than the input. (C) is developed by collector current in the collector load resistor. (D) is developed across the base resistor.

9. A ☒ B ☐ C ☐ D ☐
The most common transistor amplifier configuration is the
(A) common-emitter. (B) common-base. (C) common-collector. (D) emitter-follower.

10. A ☒ B ☐ C ☐ D ☐
Assume that the circuit of Figure 14 is operating properly. If a short is placed from base to emitter on Q_1, collector current will
(A) drop to near zero. (B) increase to a high value. (C) decrease slightly. (D) increase slightly.

GUIDE SHEETS FOR EXPERIMENTS
9504 SERIES

BASIC AMPLIFIER CIRCUITS

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MATERIALS

THIS LIST INCLUDES ALL TOOLS, HARDWARE AND ELECTRONIC COMPONENTS NEEDED TO COMPLETE THE EXPERIMENTS IN THIS MANUAL.

1 - Multimeter with Test Leads and Spring Adapters
1 - Soldering Iron
1 - Pair Long-Nose Pliers
1 - Pair Wire Cutters
1 - 9-Pin Tube Socket
1 - 5 kΩ Potentiometer
1 - 1 MΩ Potentiometer
2 - Potentiometer Mounting Brackets
1 - Transistor Socket
4 - Tri-Mounts
1 - NPN Transistor
1 - PNP Transistor
17 - Modular Connectors
1 - Silicon Diode
1 - 12AU7 Tube
1 - 470Ω, 1/2 W, 20% Resistor
1 - 1 kΩ, 1/2 W, 20% Resistor
1 - 4.7 kΩ, 1/2 W, 20% Resistor
2 - 10 kΩ, 1/2 W, 20% Resistors
1 - 22 kΩ, 1/2 W, 20% Resistor
1 - 100 kΩ, 1/2 W, 20% Resistor
1 - 220 kΩ, 1/2 W, 20% Resistor
1 - 470 kΩ, 1/2 W, 20% Resistor
1 - 1 MΩ, 1/2 W, 20% Resistor
1 - 10 μF, 50 Volt Electrolytic Capacitor
- No. 22 Solid Hookup Wire Consisting of 12 1/4" Black, 2" Red, 12" Green, 10" Blue, 4" Yellow
- Rosin Core Solder Type 60/40 Size .032

INTRODUCTION

COMPONENT PREPARATION

PARTS NEEDED

1 - Transistor Socket
1 - Soldering Iron
1 - Pair Long-Nose Pliers
1 - Pair Wire Cutters
1 - 9-Pin Tube Socket
1 - 5 kΩ Potentiometer
1 - 1 MΩ Potentiometer
- No. 22 Solid Hookup Wire
- Solder
2 - Potentiometer Mtg. Brackets

OBJECTIVE

In the following steps you will attach wire leads to a transistor socket, tube socket and potentiometers, permitting them to be easily connected to the modular connectors on the design console.

PART 1

PROCEDURE

WIRING THE TRANSISTOR SOCKET

1. Pick out the transistor socket and compare it with Figures 1A and 1B. The socket has three lugs coming out of its base. Wire leads will be soldered to these lugs.

2. Bend each of the lugs coming out of the base of the socket in the shape of a hook, as shown in Figure 2.

3. From your supply of hookup wire, cut three 2" pieces of wire of the colors shown in Figure 2.

4. Remove 1/4" of insulation from one end of each of the three pieces of wire. Remove 1/2" of insulation from the remaining unstripped ends.

5. Bend the ends from which 1/4" of insulation was stripped into the shape of a hook, as in Figure 2.

6. Following Figure 2, slip the hooked end of each of the wires over the hooked ends of the lugs from the base of the socket. Crimp the hooked end of the wire and lug together so each connection is secure. Be sure that the red wire is connected to the collector lug, the green wire is connected to the base lug, and the black wire is connected to the emitter lug.

7. Solder the three connections.

PART 2

PROCEDURE

WIRING THE TUBE SOCKET

1. Referring to Figure 3, connect and solder the leads to the tube socket lugs as instructed in the following steps.

2. Cut a 2-1/2" length of black hookup wire. Remove 1/2" of insulation from each end. Connect one end to lug 4 and then to lug 5 of the tube socket as shown in Figure 3. Solder lugs 4 and 5.

3. Cut 2-1/4" leads of the other colors as shown in Figure 3, and remove 1/4" of insulation from one end and 1/2" from the other end. Connect the 1/4" ends of the leads to the other socket lugs as shown. Solder each of the seven lugs.

4. Referring to Figure 4, bend each of the nine lugs at about a 45° angle as shown. DO NOT bend the guide lug.

5. Notice that the lugs are numbered clockwise, starting from the guide lug, as you look at the bottom of the socket. Therefore, from the top of the socket, they are numbered counterclockwise.

PART 3

PROCEDURE

WIRING THE POTENTIOMETERS

1. Referring to Figures 5 and 6, mount the 5 kΩ potentiometer to a mounting bracket as shown. (The 5 kΩ potentiometer is identified by the value stamped on the case.) To hold the pot to the bracket, twist the two mounting tabs with your long-nose pliers. A twist of 45° should be sufficient to secure the potentiometer to the bracket.

2. In the same manner, mount the 1 MΩ potentiometer to the remaining bracket. (The 1 MΩ potentiometer is identified by a value stamped on the case.)

3. Cut 3" lengths of blue, green and black hookup wire. Remove 1/4" of insulation from one end of each and 1/2" from the other end of each. Connect the 1/4" ends to the lugs of the 5 kΩ potentiometer as indicated.

4. Apply solder to each of the three lugs of the potentiometer.

5. Prepare the 1 MΩ potentiometer in the same way, and solder each of the three lugs.

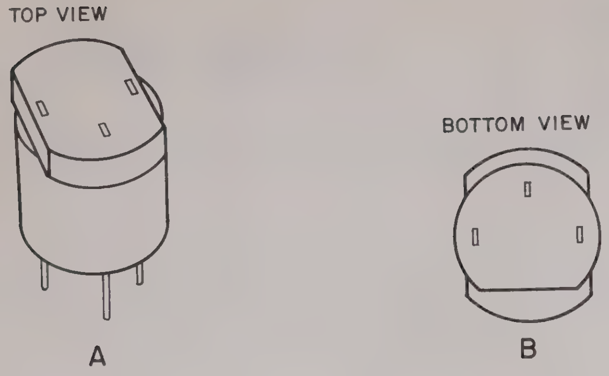
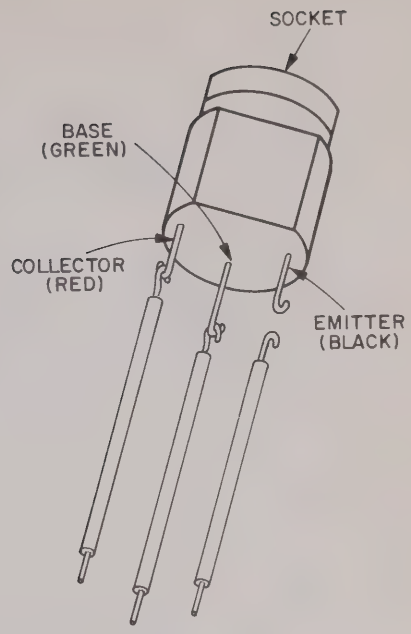


FIGURE 1



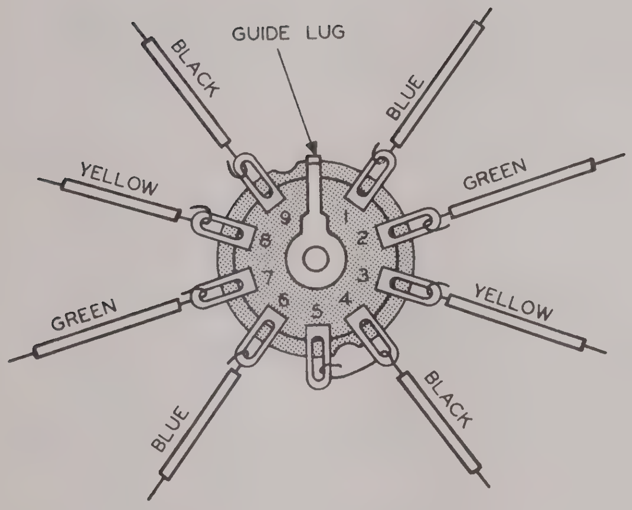


FIGURE 3

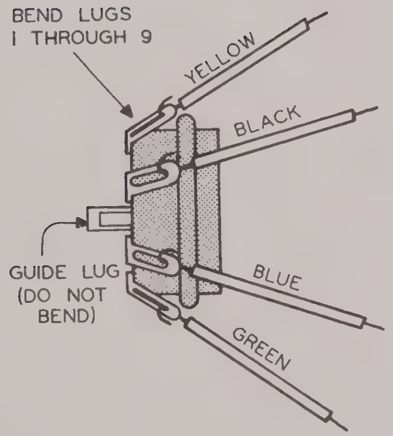


FIGURE 4

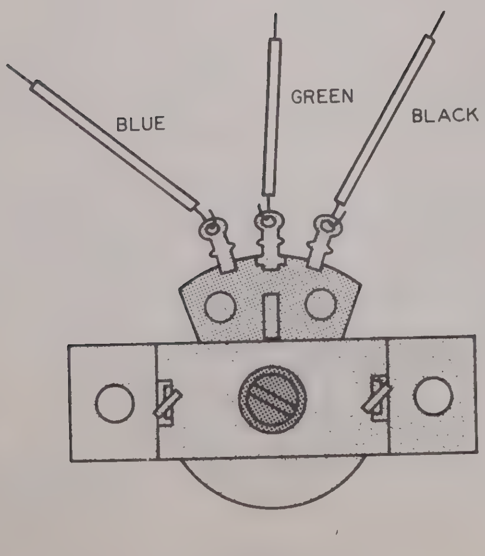


FIGURE 5

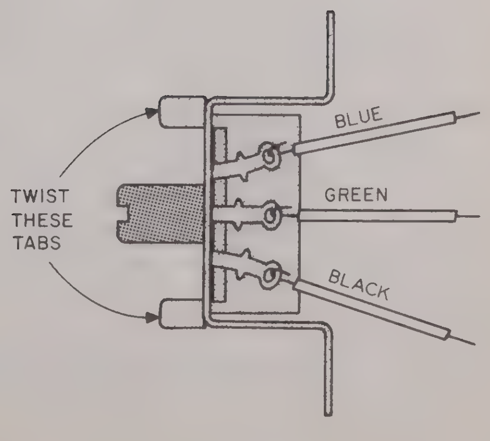


FIGURE 6

NOTES

EXPERIMENT 1

TRANSISTOR CIRCUITS - IDENTIFYING TRANSISTOR TYPES

PARTS NEEDED

1 - Multimeter with Test Leads and Test Prod Spring Adapters
1 - Partially Completed Design Console
1 - NPN Transistor (Silicon)
1 - PNP Transistor (Germanium)
9 - Modular Connectors
1 - Transistor Socket with Leads

OBJECTIVE

In this experiment you will learn how to identify a PNP and an NPN transistor by using your ohmmeter. Besides identifying the type of a transistor, the ohmmeter readings can provide an indication of the operating condition of the transistor.

PART 1

PROCEDURE

1. Figure 1-1 shows a number of the more common transistor case configurations (shown approximately full size). Cases A through G are generally used for low power (or as "small signal") transistors while cases H through L are used for high power transistors. Note that the lead arrangement of the base, emitter, and collector depends upon the case style.

2. Select the two transistors from your supply of components and compare them to Figure 1-1. The figure shows the side and bottom views of several popular cases. The transistors in your supply of parts should have the appearance of case style A, case style C or case style D. The style A case is generally referred to as the TO-5 (some of which have the collector connected to the case) case and the style C and D cases are referred to as the TO-92 and TO-98 cases, respectively. Style B is a TO-18 case, style F is a TO-105 case, style H is a TO-3 case, and style I is a TO-36 case. Plastic cases are used for styles C, D, F, K and L. Some transistors with the same transistor number from different manufacturers can have different case styles. Note that some transistor cases, such as styles C and E, can have different lead arrangements.

3. If the transistor leads are short, the socket wired earlier should be employed. Plug one of the two transistors into the socket, referring to the diagram of Figure 1-2 for the correct lead insertion. Then connect the transistor socket to three modular connectors, as shown in the layout of Figure 1-3. If your transistors have long leads which are difficult to plug into the socket, the leads can be inserted directly into the modular connectors.

4. An ohmmeter includes a dc power source which can be used to forward bias

and reverse bias the transistor PN junctions and thus measure the forward and reverse junction resistance.

Reviewing the basic characteristics of a PN junction, you will recall that to forward bias a PN junction, the P material is made positive with respect to the N material. For reverse bias, the opposite polarity is applied. When forward biased, the junction resistance is low; when reverse biased, the junction resistance is high.

5. Refer to the instruction manual for your multimeter and record the ohmmeter polarity here for your reference.

Red Test Lead Polarity —

Black Test Lead Polarity +

Now using the ohmmeter set to the highest resistance range, measure the base-to-emitter resistance with the red test lead on the base and the black test lead on the emitter.

Base-to-Emitter Resistance 500 ohms

(Red Lead to Base -- Black Lead to Emitter)

6. Reverse the ohmmeter leads at the transistor and remeasure the base-to-emitter resistance.

Base-to-Emitter Resistance 1 M ohms

(Black Lead to Base -- Red Lead to Emitter)

7. One of the resistance measurements should be high and the other should be low since the ohmmeter is forward biasing the PN junction in one case and reverse biasing the PN junction in the other case. Since we know the polarity of the ohmmeter, recorded in Step 5, we can determine which type this transistor is: an NPN or a PNP.

Let's assume that our meter polarity is such that the red lead is negative and the black lead is positive. Now, if we obtained a low resistance reading with the red lead on the base and the black lead on the emitter, the transistor must be a PNP type. The negative voltage at the red lead forward biases the base-to-emitter junction.

On the other hand, if we obtained a low reading when the black lead was on the base and the red lead was on the emitter, the transistor type is NPN. Now the positive voltage from the black lead connected to the base forward biases the base-to-emitter junction. If the ohmmeter polarity were opposite, then the above procedure would be reversed.

8. Using the procedure just described, determine whether the transistor you checked was a PNP or an NPN. You might label the transistor with a piece of tape. The part number on the transistor should also be recorded for future reference.

First Transistor Type PNP Part No. 2N404

9. The base-to-collector junction can also be measured with the ohmmeter to determine the type of transistor. Measure the base-to-collector resistance with the leads both ways and record below.

Base-to-Collector Resistance 500 ohms

(Red Lead to Base -- Black Lead to Collector)

Base-to-Collector Resistance 1·M ohms

(Black Lead to Base -- Red Lead to Collector)

10. Using the above resistance readings, confirm your earlier determination of whether the transistor was an NPN or a PNP.

CONCLUSION

Either the base-to-emitter or the base-to-collector junction resistance can be used to determine whether the transistor is a PNP type or an NPN type. The determination is based upon the ohmmeter battery forward and reverse biasing the base-emitter or base-collector junction.

PART 2

PROCEDURE

1. Select the other transistor from your supply of components and, after removing the first transistor, connect the second transistor in its place. Refer to Figure 1-2 for the lead insertion.

2. Using the ohmmeter, measure the base-emitter and base-collector resistance of the transistor with the ohmmeter connected both ways. Record your readings below.

Base-Emitter Resistance ∞ ohms

(Red Lead to Base -- Black Lead to Emitter)

Base-Emitter Resistance 6K ohms

(Black Lead to Base -- Red Lead to Emitter)

Base-Collector Resistance ∞ ohms

(Red Lead to Base -- Black Lead to Collector)

Base-Collector Resistance 6K ohms

(Black Lead to Base -- Red Lead to Collector)

3. Using the resistance readings from Step 2, determine which type the transistor is: an NPN or a PNP. Record this data along with the part number below. You may wish to label each transistor with a piece of tape.

Second Transistor Type NPN Part No. 2N3393

CONCLUSION

One of the transistor types should be a PNP and the other should be an NPN. Either the base-to-emitter or base-to-collector junction can be measured to determine the type. By measuring both the junctions, you can also roughly determine whether the transistor is good or bad. If a transistor is good, you will obtain a low reading on both junctions with the leads one way and a high resistance with the leads the other way. If the readings both ways are high or low (or equal), the transistor is defective.

The actual resistance readings you obtain from the base-to-emitter and base-to-collector junctions depend upon the transistor and differ even for transistors having the same number. The chart of Figure 1-4 shows some typical resistance readings for germanium and silicon transistors.

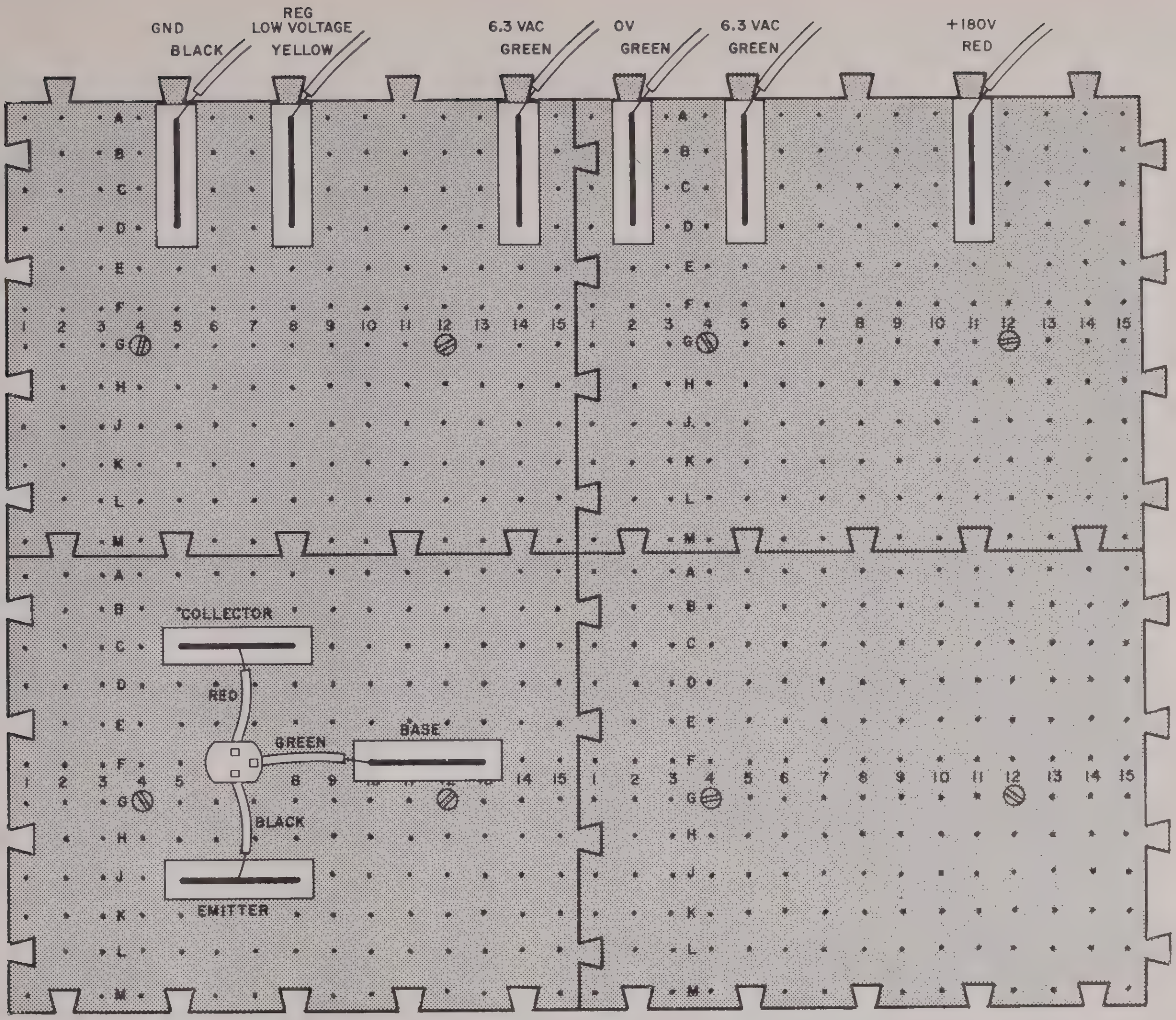


FIGURE 1-3

Transistor Type		Ohmmeter Connections		Resistance In Ohms
		+ Lead	- Lead	
Germanium PNP	Power	Emitter Emitter	Base Collector	30Ω to 50Ω Several Hundred
	Small Signal	Emitter Emitter	Base Collector	200Ω to 250Ω 10K to 100 kΩ
Silicon PNP	Small Signal	Emitter	Base	1K to 10 kΩ
		Emitter	Collector	Very High (Might Read Open)
Silicon NPN	Power	Base	Emitter	200Ω to 1000Ω
		Collector	Emitter	High, Often Greater Than 1 MΩ
	Small Signal	Base	Emitter	1K to 3 kΩ
		Collector	Emitter	Very High (Might Read Open)

TYPICAL TRANSISTOR JUNCTION RESISTANCE VALUES

Figure 1-4

NOTES

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EXAMINATION CHECK SHEET

1. B - TO FORWARD BIAS A PN JUNCTION, -- THE N MATERIAL IS MADE NEGATIVE AND THE P MATERIAL IS MADE POSITIVE.
For a silicon transistor, the forward bias is 0.6 volt and for a germanium transistor the forward bias is approximately 0.2 to 0.3 volt.

2. C - WHEN A PN JUNCTION IS FORWARD BIASED, ITS RESISTANCE WOULD BE -- IN THE RANGE OF 50 OHMS TO 5K OHMS.
A reverse biased PN junction has a very high resistance.

3. A - USING AN OHMMETER TO CHECK A TRANSISTOR, IF THE OHMMETER POLARITY IS POSITIVE ON THE RED LEAD AND NEGATIVE ON THE BLACK LEAD, AN NPN TRANSISTOR WILL READ -- A LOW RESISTANCE WITH THE RED LEAD ON THE BASE AND BLACK LEAD ON THE EMITTER.
The low resistance is obtained since the ohmmeter is forward biasing the PN junction.

4. D - WHEN USING A MULTIMETER TO CHECK THE CONDITION OF A TRANSISTOR BY MEASURING THE FORWARD AND REVERSE JUNCTION RESISTANCE, A GOOD TRANSISTOR IS ONE WITH -- LOW FORWARD AND HIGH REVERSE RESISTANCE.
The transistor is defective if both readings are high or low.

5. B - TO PROPERLY BIAS A TRANSISTOR FOR NORMAL OPERATION, THE -- BASE-TO-EMITTER JUNCTION IS FORWARD BIASED AND THE BASE-TO-COLLECTOR JUNCTION IS REVERSE BIASED.
If any other bias arrangement is employed, the transistor will not amplify.

TRANSISTOR CHARACTERISTICS

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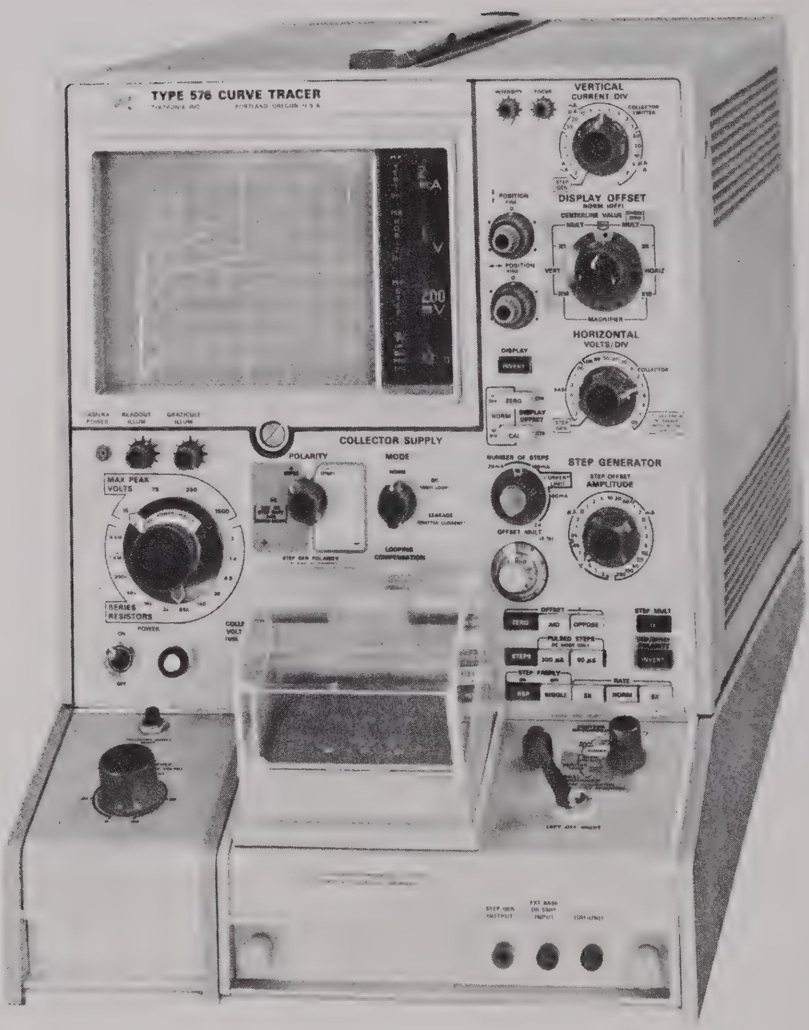

The curve tracer shown above automatically generates a family of characteristic curves for the device under test. A camera can be attached to the curve tracer to obtain a permanent record of the curves.

Courtesy Tektronix, Inc.

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> *But whether or not our efforts bear fruit, let us be able to say, when we come near the great goal, "I have done what I could."*
> *—Louis Pasteur*

TRANSISTOR CHARACTERISTICS

To understand the operation of transistor circuits, it is first necessary to understand the characteristics of a transistor. By characteristics we mean how the collector current varies with changes in base current and collector-to-emitter voltage. The characteristics of a transistor can be illustrated both mathematically and graphically. The graphical method is much simpler and will be used in this lesson.

When the characteristics of a transistor are shown graphically, we call the graph a **CHARACTERISTIC CURVE**. The characteristic curves are generally supplied by the manufacturer of the transistor. Since the characteristics vary from device to device, the characteristics are generally specified as AVERAGE.

COMMON-EMITTER CIRCUITS

One of the most common transistor circuits is the common-emitter configuration shown in Figure 1. In the common-emitter circuit, the emitter is the common element between the input and output circuits. In Figure 1, the base current (I_B) is considered as the input current, and the collector current (I_C) is the output current. Both base and collector currents flow through the emitter.

Characteristic Curves

The characteristics of a transistor depend upon the circuit configuration. Thus, the characteristics of a transistor in a common-base and common-emitter configuration are not the same.

Let's examine the characteristics of the transistor in Figure 1. Collector current is directly proportional to base current. Thus, increasing base current increases collector current, and vice versa. However, the value of collector current is also dependent upon the collector-to-emitter voltage, V_{CE}.

To analyze the action in detail, suppose that the value of base current in Figure 1 is held at some constant value, say 150 μA. If the value of V_{CE} is zero, collector current will also be zero. As V_{CE} is increased, collector current increases. However, once a certain value of V_{CE} is reached, collector current remains relatively constant. The transistor is therefore considered to be a constant current device as far as the collector-to-emitter voltage is concerned.

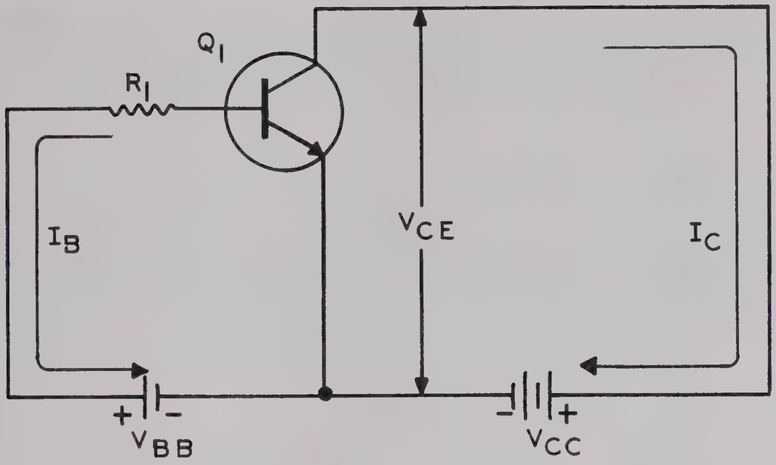


Figure 1

Figure 2 shows a graph of the characteristics of the transistor in Figure 1 at a fixed base current of 150 μA. The vertical scale along the left side represents the collector current, I_C, in milliamperes. The collector-to-emitter voltage, V_{CE}, is shown along the bottom of the graph. Since Q_1 in Figure 1 is an NPN transistor, collector voltage is positive and the collector-to-emitter voltage in Figure 2 is also shown as positive. Collector current I_C, base current I_B, and V_{CE} are sometimes shown as negative for a PNP transistor.

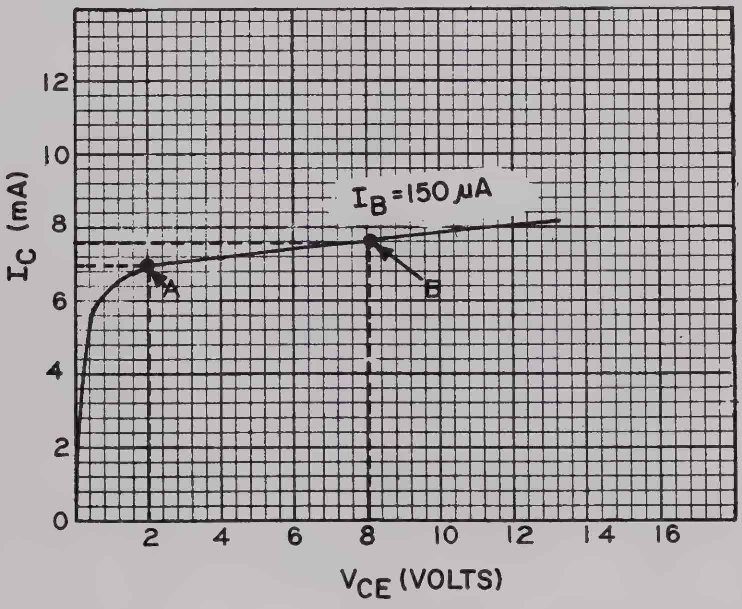


Figure 2

The graph of Figure 2 shows how collector current varies with changes in collector-to-emitter voltage with the base current held constant. This type of graph is generally referred to as a **COLLECTOR CHARACTERISTIC CURVE**. Starting out with the collector-to-emitter voltage, V_{CE}, equal to zero, the collector current, I_C, is also zero. Suppose that V_{CE} is equal to 2 volts. Drawing a line from the 2-volt point up to the curve, point A, and then over to the current scale, we see that I_C is about 7 mA. Note that the slope of the curve is quite shallow beyond the 2-volt point. That is, collector current changes very little beyond a V_{CE} of about 2 volts. For example, at a V_{CE} of 8 volts, point B on the curve, I_C has only increased to about 7.6 mA. As mentioned earlier, the transistor exhibits a somewhat constant collector current characteristic for fixed values of base current.

The graph of Figure 2, although useful, does not show how collector current varies with changes in base current. To show the effects of base current, lines representing other values of base current are drawn on the graph. This arrangement is shown in Figure 3. Since this graph includes several characteristic curves, it is often referred to as a FAMILY OF CHARACTERISTIC CURVES.

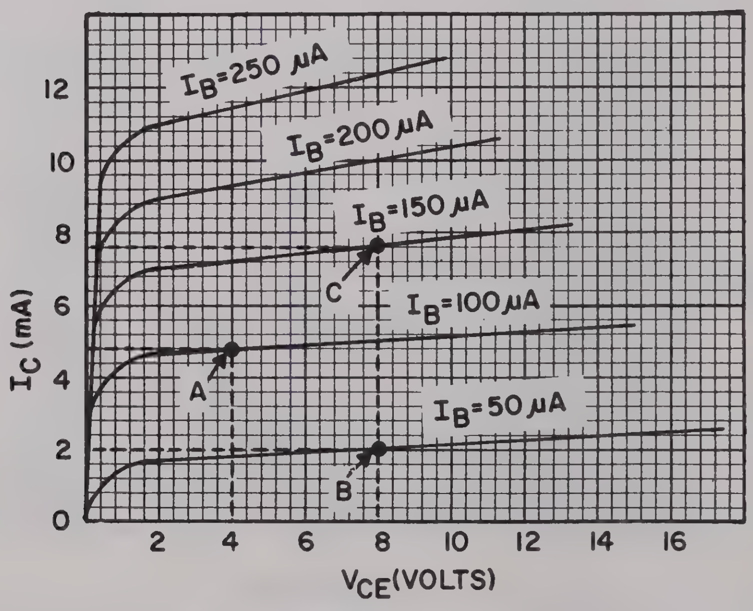


Figure 3

The value of base current I_B is shown next to each individual line or curve. Notice the curve labeled $I_B = 50$ μA. At any point on this curve, base current I_B has a value of 50 microamperes (μA). Therefore, any point on the curve labeled $I_B = 100$ μA represents a base current of 100 μA. Any point on the $I_B = 150\ \mu A$ curve represents a base current of 150 μA, and so on. Suppose the base current is 200 μA in the circuit of Figure 1. We describe this by saying we are "operating" somewhere along the curve labeled $I_B = 200\ \mu A$.

Any point on one of the I_B curves, then, shows us three important things — the base current, the collector-to-emitter voltage and the resultant collector current. For example, take point A on the $I_B = 100\ \mu A$ curve. The base current is 100 μA since point A is on the 100 μA curve. Following the dashed line from point A to the left scale, the collector current is 4.8 mA. Following the dashed line from point A to the bottom scale, the collector-to-emitter voltage is 4 volts. Thus, when the transistor has 4 volts applied to the collector and 100 μA of current is flowing in the base-emitter circuit, the collector current will be 4.8 mA.

In a common-emitter circuit such as Figure 1, base current I_B is the input current. Collector current I_C is the output current. The current in the base circuit controls the current in the collector circuit. Collector current is larger than base current. Let's take a given input current (base current I_B) and a given collector-to-emitter voltage, V_{CE}, and, using the characteristic curves of Figure 3, find the output (collector) current.

Assume that the base current caused by V_{BB} is 50 μA. The purpose of resistor R_1 in Figure 1 is to limit base current to this value. Any point on the curve $I_B = 50\ \mu A$ of Figure 3 represents a base current of 50 μA. Suppose now that V_{CC} applies 8 volts from the collector to the emitter of transistor Q_1. This is the voltage (V_{CE}) shown by the scale at the bottom of Figure 3. To find the collector current, follow the dashed line up from the 8-volt point on the V_{CE} scale to point B, where the dashed line intersects or crosses the $I_B = 50\ \mu A$ curve. Point B is called the operating point for this base current and collector voltage. From this point of intersection, follow the horizontal dashed line to the left to the I_C scale. The I_C value at this point is 2 mA.

Thus, in the circuit of Figure 1, with a base current of 50 μA and a collector-to-emitter voltage (V_{CE}) of 8 volts, the current in the collector circuit (I_C) is 2 mA. Notice that the output collector current of 2 mA is much larger than input base current of 50 μA.

Suppose now that we replace battery V_{BB} in Figure 1 with a larger battery that causes 150 μA of base current. How much collector current will flow in the circuit if the value of V_{CE} remains 8 volts? Follow the dashed line up from the 8-volt point on the scale to point C, where the dashed line intersects the $I_B = 150\ \mu A$ curve. Then follow the dashed line from point C to the I_C scale. The line meets the I_C scale at the 7.6 mA point.

This example shows that, with an I_B of 150 μA and a V_{CE} of 8 volts in Figure 1, an I_C of 7.6 mA flows in the collector circuit. Thus, if we know the base current and the collector voltage of a circuit like that of Figure 1, by using the characteristic curves of the transistor, we can determine the collector current. Or, if the desired value of output current is known, we can find the value of input current needed to produce it.

In the previous examples, different values of base current resulted in different values of collector current. With battery V_{CC} providing 8 volts between the collector and emitter, a base current of 50 μA (point B) resulted in 2 mA of collector current. When the base current was changed to 150 μA (point C), the collector current became 7.6 mA.

Changing base current from 50 μA to 150 μA made the collector current change from 2 mA to 7.6 mA. THIS IS IMPORTANT. A change of only 100 μA (150 μA — 50 μA) in the base circuit caused a collector current change of 5.6 mA (7.6 mA — 2 mA). **A SMALL CHANGE IN BASE CURRENT CAUSES A LARGE CHANGE IN COLLECTOR CURRENT**. This is one reason why transistors are so useful. Changes of base current are amplified in the collector circuit. With a family of curves such as those shown in Figure 3, you can tell exactly how much amplification a given type of transistor provides.

Operating Point

Figure 4 shows the schematic diagram of another transistor circuit, and Figure 5 shows a group of curves to use with the transistor of this schematic.

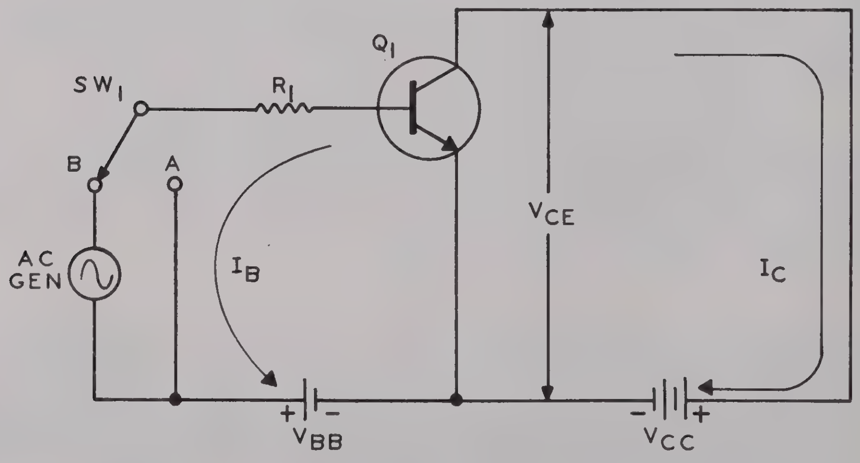


Figure 4

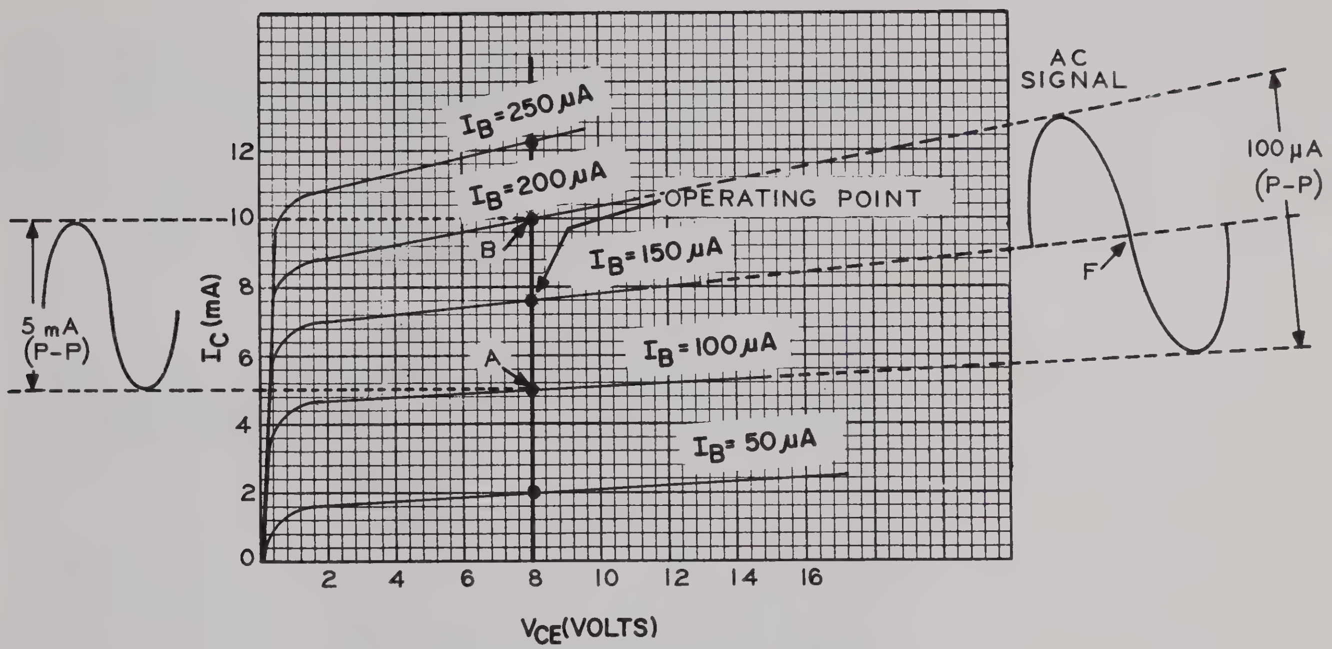


Figure 5

In the circuit of Figure 4, V_{CC} applies 8 volts from the collector to the emitter of transistor Q_1. On the curves of Figure 5, the solid line drawn vertically from the 8-volt point of the V_{CE} scale represents this condition. At any point along this line, collector-to-emitter voltage V_{CE} equals 8 volts. As long as the battery remains at this voltage, the transistor must operate along this 8-volt line.

Figure 4 includes an ac generator which may be switched into the circuit by switch SW_1. Assume that switch SW_1 is in position A. In this switch position, the ac generator is not connected to the circuit. Also assume that V_{BB} causes 150 μA of base current in the base circuit. You can find the collector current in Figure 4 by following the 8-volt V_{CE} line up to where it intersects the $I_B = 150\ \mu A$ curve. This point is the **OPERATING POINT**. Following the horizontal line to the left from the operating point, the collector current equals 7.6 mA. This is the current in the collector circuit of Figure 4 under the stated conditions.

Current Gain h_{fe}

Suppose switch SW_1 is now changed to position B (as shown) so that the ac generator is connected in the base-emitter circuit of Q_1. The generator is now in series with V_{BB} between the emitter and base of transistor Q_1. The dc base current caused by V_{BB} is 150 μA, and the alternations of the generator cause the base current to increase and decrease around this level.

Assume that, when the polarity of the ac generator aids V_{BB}, the base current increases to 200 μA, and the opposite alternation causes the base current to decrease to 100 μA. This is shown at the right of Figure 5 by extending the base current curves and drawing the ac signal from the generator between 100 μA and the 200 μA curves. Notice that this is a 100 μA change in base current. We can say that the generator output is 100 μA peak-to-peak. This is then called a 100 μA peak-to-peak input signal.

When the base current changes, the collector current also changes. The amount of collector current change can easily be determined from the curves of Figure 5. Remember, V_{CC} provides a steady 8 volts between collector and emitter. Remember also that the base current changes from 100 μA to 200 μA during each cycle of generator voltage. Point A in Figure 5 corresponds to $V_{CE} = 8$ volts and $I_B = 100$ μA. The collector current at this instant is found by following the dashed line from point A to the left margin. Reading the I_C scale, the collector current is 5 mA when $I_B = 100$ μA.

Point B of Figure 5 corresponds to $V_{CE} = 8$ volts and $I_B = 200$ μA. This is the other peak of the input signal to the base. The collector current at this instant is found by following the dashed line from point B to the left margin. Collector current is shown as 10 mA. The collector current changes from 5 mA to 10 mA. The peak-to-peak collector current change is 10 mA — 5 mA = 5 mA.

Thus, the input current change of 100 μA peak-to-peak produces a collector current change of 5000 μA peak-to-peak. The comparison of collector current change to base current change is very important. This is called **CURRENT GAIN** of a common-emitter amplifier and is usually identified by the symbol h_{fe}. The small e in the subscript indicates a common-emitter circuit.

Current gain, h_{fe}, is equal to the change in collector current divided by the change in base current:

$$h_{fe} = \frac{\Delta I_C}{\Delta I_B} \tag{1}$$

where: Δ (delta) means a "small change of."

In the circuit of Figure 4, the change in I_C is about 5000 μA and the change in I_B is 100 μA. Substituting in the equation:

$$h_{fe} = \frac{5000\ \mu A}{100\ \mu A} = 50.$$

Thus, the transistor of Figure 4 has a current gain, h_{fe}, of 50. You will sometimes see current gain, $\mathbf{h}_{fe}$, indicated by the Greek letter **BETA (β)**.

What does a current gain, h_{fe}, of 50 indicate? This simply means that any small change of base current will cause a change of collector current 50 times greater. For example, a 10 μA change in base current will cause a 500 μA change in collector current.

The definition of h_{fe} is true only when the following conditions occur:

A CONSTANT COLLECTOR VOLTAGE IS USED WHEN DETERMINING h_{fe}. This has been shown by the vertical line in Figure 5, which represents a constant collector voltage. You will see why this is important later.

CHANGES IN BASE CURRENT MUST BE SMALL NEAR A GIVEN OPERATING POINT. Since the spacing between the characteristic curves varies, different values for h_{fe} could be arrived at by comparing large changes in base current. This could result in false values for h_{fe}.

THE h_{fe} OF A GIVEN TRANSISTOR TYPE IS ONLY A TYPICAL OR AVERAGE VALUE. Therefore, the h_{fe} of a given transistor may range above or below this average value. Manufacturers often indicate how far above or below this average value the actual h_{fe} of their transistors may range.

Load Lines

We have shown that a transistor provides an output current which, in a common-emitter circuit, is collector current I_C. In many applications, it is necessary for the transistor to provide an output voltage. This is accomplished by inserting a resistor between the collector and the collector supply. The collector current passes through this resistor and develops a voltage across it which is proportional to the collector current. Figure 6 shows a resistor, R_L, placed in the collector circuit. This resistor is generally known as the load resistor. This circuit is almost the same as the circuit of Figure 4 with switch SW_1 in the B position, but load resistor R_L has been added in the collector circuit. Collector current I_C, passing through load resistor R_L, develops the output voltage (E_O) of the circuit.

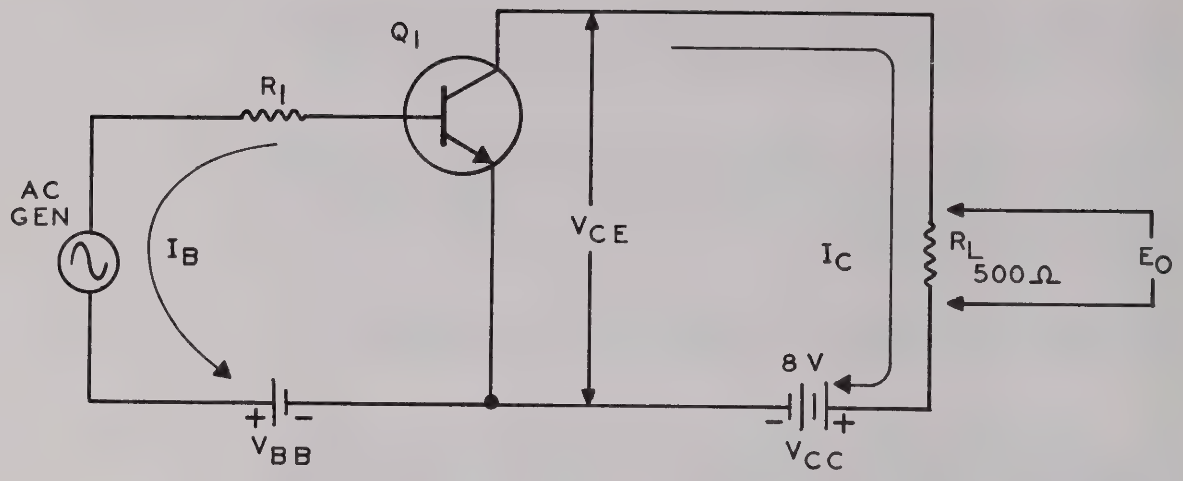


Figure 6

In the circuit of Figure 4, if V_{CC} is an 8-volt battery, the collector-to-emitter voltage (V_{CE}) is always 8 volts, and can be represented by the vertical line drawn in Figure 5. In the circuit of Figure 6, this is no longer true. With the addition of the load resistor, the collector-to-emitter voltage, V_{CE}, is no longer constant when there is collector current. The collector supply voltage (V_{CC}) is divided between the load resistor (R_L) and the collector-to-emitter resistance of the transistor. The greater the collector current, the greater the voltage developed across R_L, and the smaller the voltage between the collector and emitter of transistor Q_1.

Instead of representing operating conditions by a vertical line as in Figure 5, we must represent them by a slanted line when a load resistor is included in the circuit. These slanted lines, shown in Figure 7, are known as **LOAD LINES.** The amount of slant, or slope, of a load line depends solely upon the size of the load resistor, R_L.

As the resistance of the load resistor is increased, the slope of the load line decreases. In Figure 7, load line 2 represents a larger value load resistor in the circuit than does load line 1. The largest value of load resistance is represented by load line 4.

A load line is very easy to construct. Let's construct the load line for the circuit of Figure 6 on the curves of Figure 8. Suppose that R_L in Figure 6 has a value of 500Ω, as shown, and the collector supply voltage provided by V_{CC} is 8 volts. To draw the load line, two points must be found. The first point to find is the OPEN CIRCUIT POINT. This point is found by assuming a collector current of zero. With I_C equal to zero, there is no

The following Practice Exercise questions cover the subjects which you have just studied. They are:

COMMON-EMITTER CIRCUITS

CHARACTERISTIC CURVES

OPERATING POINT

CURRENT GAIN h_{fe}

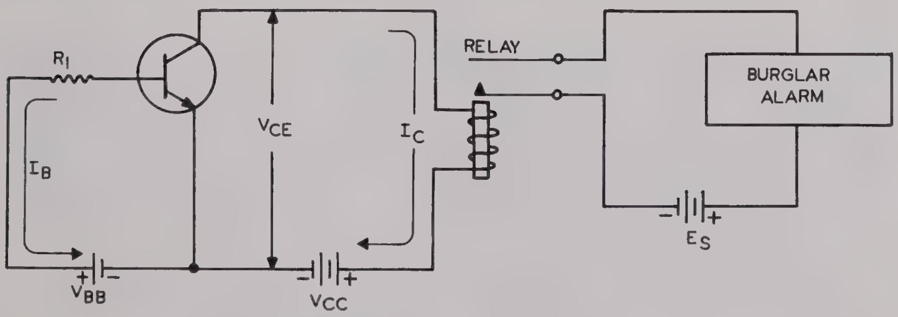
1. How does collector current vary with changes in base current and collector-to-emitter voltage?

2. Where does the greatest change in collector current occur in the graph of Figure 2?

3. What is the graph of Figure 3 called?

4. Using Figure 3, if V_{CE} is 8 volts and I_B is 200 μA, what is the value of collector current I_C?

5. In the circuit below, I_C must be 12.4 mA to energize the relay and ring the bell. V_{CE} is 8 volts. Using the curves of Figure 3, what value of I_B is needed to ring the bell?



6. The characteristic curves of Figure 3 are for a (a) common-emitter circuit, (b) common-base circuit, (c) common-collector circuit.

7. **The term h_{fe} represents the current gain of a common-emitter transistor amplifier such as shown in Figure 4. True or False?**

8. **Define h_{fe} in terms of collector current and base current.**

9. **Suppose that the base current in Figure 4 varies from 50 μA to 150 μA, and V_{CE} is a constant 8 volts. Using the characteristic curves of Figure 5, what is the change in collector current (I_C) in milliamperes?**

10. **In Practice Exercise 9, what is the current gain (h_{fe})?**

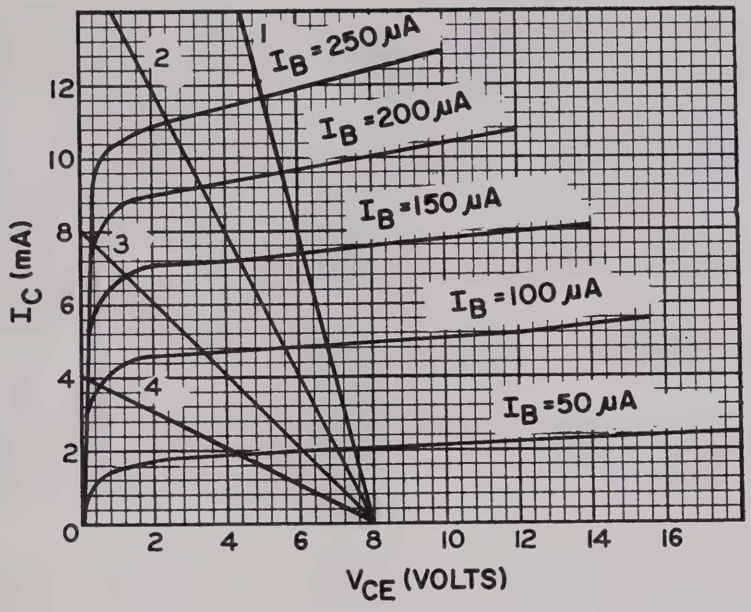


Figure 7

voltage drop across R_L, and the entire supply voltage appears across the transistor. The open circuit point thus occurs at I_C equal to zero and V_{CE} equal to the collector supply, 8 volts, or point D in Figure 8.

The second point for the load line is called the SHORT CIRCUIT POINT and is found by determining the maximum value of collector current. In the circuit of Figure 6, the value of R_L and V_{CC} determines the maximum I_C. To determine the maximum value of I_C, assume that the transistor is a short between collector and emitter: that is, V_{CE} equals zero. Under these conditions, I_C is equal to V_{CC}/R_L = 8 volts/500Ω = 16 mA. Thus, the second point for the load line is I_C = 16 mA and V_{CE} = 0 volts.

Notice that the collector current scale on the curves of Figure 8 does not go to 16 mA. Thus, you cannot plot the short circuit point on these curves. This situation may occur with some curves. When it does, just choose a value of I_C less than the short circuit current, that can be found on the curve. Let's take a value of 12 mA. With I_C equal to 12 mA, the voltage drop across R_L is equal to:

$$\begin{aligned} E_{R_L} &= R_L \times I_C \\ &= 500\Omega \times 12 \text{ mA} \\ &= 500 \times 12 \times 10^{-3} \\ &= 6 \text{ volts.} \end{aligned}$$

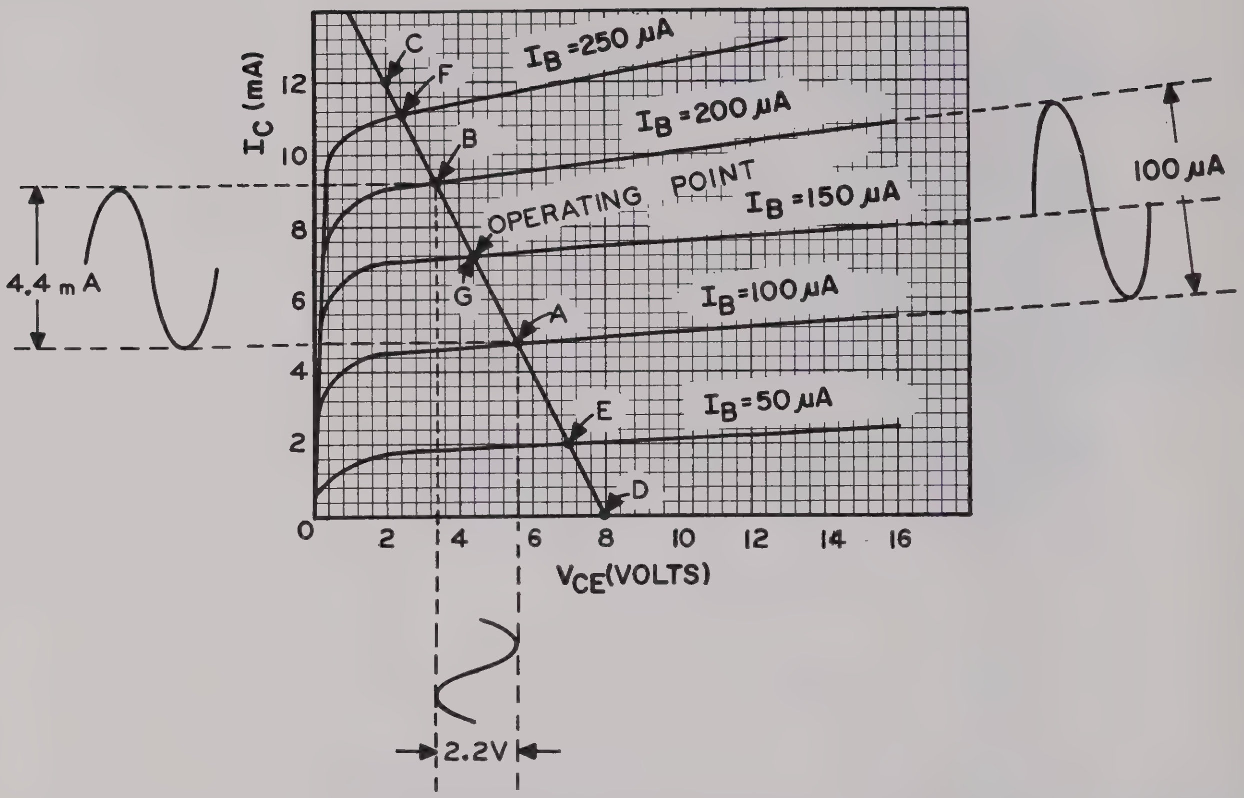


Figure 8

With the voltage across R_L equal to 6 volts, the collector-to-emitter voltage is the supply voltage minus E_{R_L}, or 8 volts — 6 volts = 2 volts. The second load line point is therefore: $I_C = 12$ mA and $V_{CE} = 2$ volts, or point C in Figure 8. The load line for $R_L = 500$ ohms is then constructed by drawing a line from point D through point C to the top of the graph. The load line represents the possible values of I_C and V_{CE} with a load of 500Ω. If R_L had a lower value, the load line would be steeper, like line 1 in Figure 7. A higher value of R_L would reduce the slope of the line, as shown by lines 3 and 4 in Figure 7.

In summary, the two load-line end points are found as indicated in Chart 1 below:

LOAD LINE POINT	I_C	V_{CE}
OPEN CIRCUIT	0	V_{CC}
SHORT CIRCUIT	V_{CC}/R_L	0

CHART 1

To illustrate how the load line can be used to examine circuit operation, suppose that V_{BB} in Figure 6 causes 150 μA of base current in the base circuit of transistor Q_1. In Figure 8, the intersection of this 150-μA base current curve and the 500-ohm load line is the operating point, G, of the circuit. Again, let's assume that the base current change has a 100 μA peak-to-peak amplitude. The alternating current applied to the input of transistor Q_1 by the ac generator causes the base current of Figure 6 to change from 100 μA to 200 μA. This change is shown at the right of the characteristic curves of Figure 8.

The 100-μA I_B curve and the load line intersect at point A. Point A then shows the lowest value of collector current which flows in the circuit. The dashed line drawn to the left from point A shows that this value of collector current is 4.8 mA.

The 200-μA I_B curve and the load line intersect at point B. By following the dashed line drawn to the left from point B, we find the maximum collector current to be 9.2 mA. Thus, collector current varies from 4.8 mA to 9.2 mA. This is a change of 4.4 mA, or 4400 μA. A 100 μA peak-to-peak base current change causes a 4400 μA peak-to-peak collector current change.

Collector current passes through load resistor R_L in the collector circuit and develops the output voltage. This voltage can be computed by using Ohm's Law ($E = IR$). Collector current changes 4.4 mA (.0044 amp) through the 500-ohm load resistor, R_L. The output voltage change is:

$$V = .0044 \times 500 = 2.2 \text{ volts.}$$

The output voltage change can also be found directly from the curves of Figure 8. Follow the dashed lines downward from points A and B to the V_{CE} scale at the bottom of the graph. The V_{CE} values at points A and B are 5.6 and 3.4 volts, respectively. This means the voltage changes from 5.6 volts to 3.4 volts, or 2.2 volts peak-to-peak. This is the same change obtained by calculation.

This example illustrates some important facts. With a load resistor in the circuit, the collector-to-emitter voltage (V_{CE}) is less than the supply voltage (V_{CC}) whenever collector current flows through the load. The change in amplitude of V_{CE} is the same as the change in amplitude of voltage across R_L. If the voltage V_{CE} decreases, the voltage across R_L, E_{R_L}, increases, and if V_{CE} increases, E_{R_L} decreases because their sum is equal to the supply voltage.

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Transfer Characteristic Curves

While the collector characteristic curves are the most common group of characteristic curves used, there are other special types. For example, a curve which shows the relationship between base current and collector current of a common-emitter transistor circuit is shown in Figure 9. This curve is called a **TRANSFER CHARACTERISTIC CURVE.** The curve gets its name because it shows how a change in base current is "transferred" into a change in collector current.

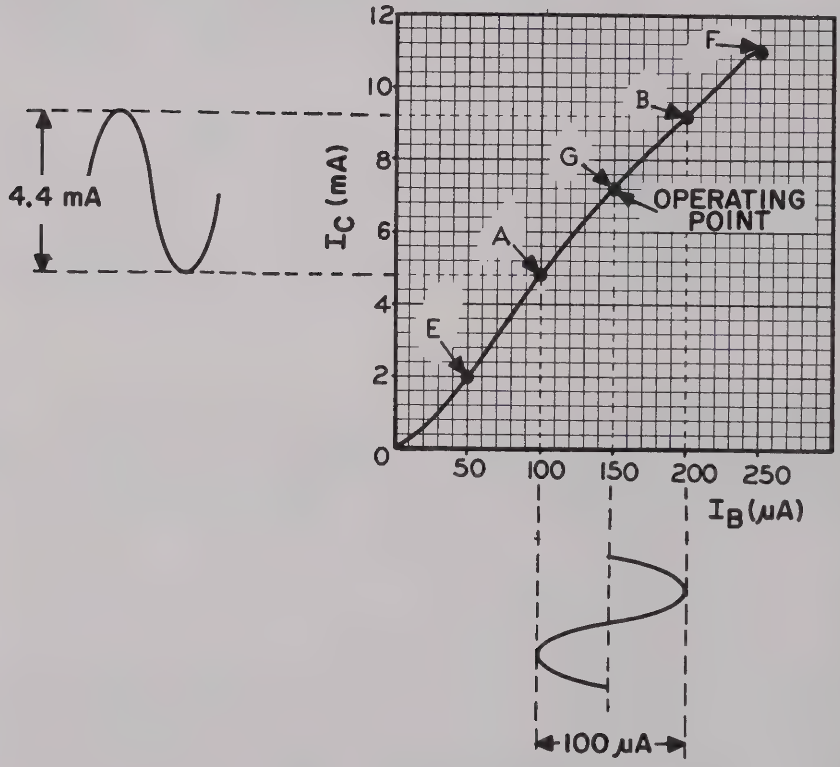


Figure 9

The transfer characteristic curve of Figure 9 is constructed from the characteristic curves and the load line of Figure 8. From the transfer characteristic curve of Figure 9, you can determine the same values as with the collector characteristic curves of Figure 8. If the base current is known, the collector current can be found. Base current (I_B) in μA is shown by the scale at the bottom of Figure 9. Collector current (I_C) in mA is indicated by the scale at the left of the figure.

The curve of Figure 9 is often simpler to use than the curves of Figure 8. It involves only one curve and two currents. You do not have to deal with collector-to-emitter voltage (V_{CE}) or a load line after the Figure 9 curve is constructed. But, to construct the curve of Figure 9, you must use the curves of Figure 8.

The transfer characteristic curve of Figure 9 is constructed from the collector characteristic curves and the load line of Figure 8. Note the points of intersection of the load line and the characteristic curves of Figure 8. These points are labeled F, B, G, A and E. The values of collector current and base current represented by these points are indicated in Figure 9. The collector current scale is exactly the same in both figures. Base current values are represented by the characteristic curves of Figure 8. Base current values of Figure 9 are represented by the scale at the bottom of the figure.

Point F of Figure 8 represents a collector current of 11.1 mA and a base current of 250 μA. In Figure 9, draw the vertical line representing a base current of 250 μA. Then draw the horizontal line which represents a collector current of 11.1 mA. These two lines intersect at point F. This locates point F on the transfer characteristic curve of Figure 9.

Point B of Figure 8 represents a collector current of 9.2 mA and a base current of 200 μA. In Figure 9, draw the horizontal line representing a collector current of 9.2 mA. Then draw the vertical line representing 200 μA base current. These two lines intersect at point B. This locates point B on the transfer characteristic curve of Figure 9.

Let's take one more point as an example. The operating point, G, of Figure 8 represents a collector current of 7.2 mA and a base current of 150 μA. In Figure 9, draw the vertical line representing a base current of 150 μA. Then draw the horizontal line representing a collector current of 7.2 mA. These two lines intersect at point G on the transfer characteristic curve of Figure 9.

If you continued this procedure for points A and E of Figure 8, you would arrive at points A and E in Figure 9. By connecting points F, B, G, A and E with a smooth curve, you can construct the transfer characteristic curve of Figure 9.

To illustrate the use of Figure 9, let's use the same operating point base current value and the same base current changes that are used in Figure 8. The operating point base current is 150 μA, and the base current has a peak-to-peak change of 100 μA. Remember, using Figure 8, we found that collector current changes 4.4 mA under these conditions. When we use the transfer curve of Figure 9, we should get the same result.

The operating point, G, is located by drawing a vertical line through the 150 μA point of the I_B scale. The 100 μA peak-to-peak base current change about the operating point causes the base current to vary from 100 μA to 200 μA. Follow the vertical dashed line representing 100 μA to point A where it intersects the transfer curve. Follow the horizontal dashed line to the left from point A. Collector current is 4.8 mA.

Now follow the vertical dashed line representing 200 μA to point B where it intersects the transfer curve. Follow the horizontal curve to the left from point B. Collector current is now 9.2 mA. Collector current varies between these two values, as shown at the left of the figure. This represents a change in collector current of 4.4 mA, or 4400 μA. This is the same result as obtained from Figure 8. The output voltage can be computed using Ohm's Law, and yields the same result as obtained previously. Notice that the change in collector-to-emitter voltage V_{CE} cannot be read directly from Figure 9 as it could be for Figure 8.

The best operating point can be seen easier from the transfer characteristic curve than it can from the collector characteristic curve. Remember, the output current is a true reproduction of the input current change only if operation is restricted to the STRAIGHTEST PART OF THE CURVE. The best operating point is then at the center of the straightest part of the transfer curve. One disadvantage of the transfer curve of Figure 9 is that it represents only one value of load resistor and one value of supply voltage. Any time the load resistor or the supply voltage is changed, a new transfer curve must be drawn.

COMMON-BASE CIRCUITS

Transistors are not only used in common-emitter circuits. When they are used in other types of circuits, different characteristic curves must be used. For example, transistors are also used in common-base circuits. Since the operating characteristics are different when a transistor is operated in a common-base circuit than when it is in a common-emitter circuit, a different set of characteristic curves must be used for each of these arrangements.

Characteristic Curves

Figure 10 shows the collector characteristic curves of the transistor used in the common-base circuit of Figure 11. These curves are for the same

The following Practice Exercise questions cover the subjects which you have just studied. They are:

COMMON-EMITTER CIRCUITS

LOAD LINES

TRANSFER CHARACTERISTIC CURVES

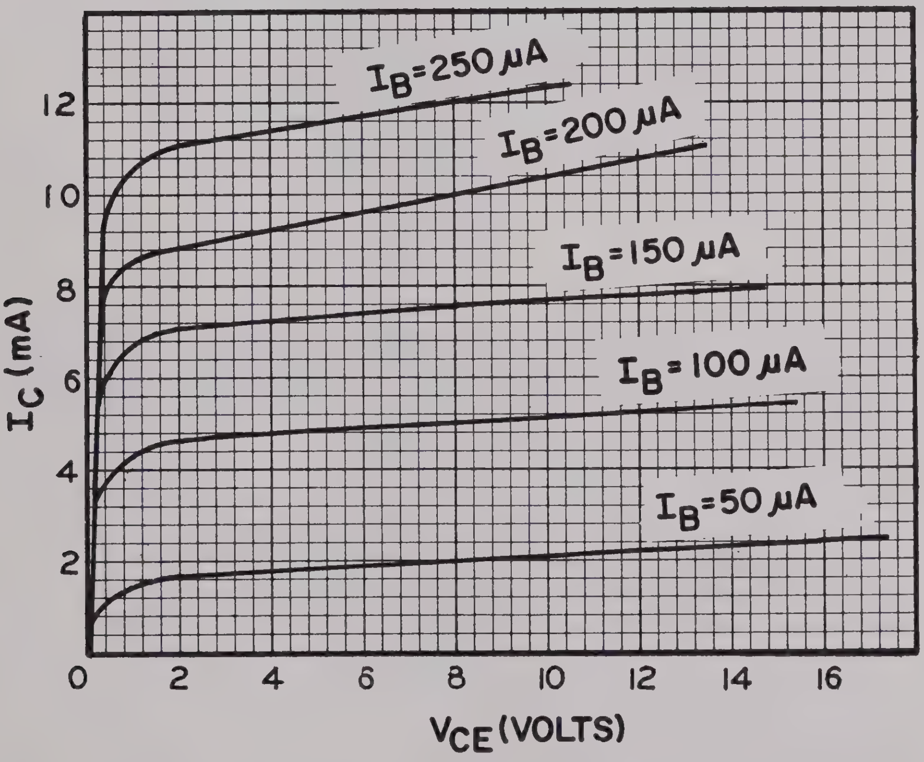
11. The slope of a load line depends only upon the type of transistor used. True or False?

12. Load line 3 of Figure 7 represents a larger value of load resistor than load line 2. True or False?

13. How are the open circuit and short circuit points for a load line found?

14. If the short circuit point cannot be plotted on the characteristic curves, how can the second point be found?

15. Suppose that V_{CC} in Figure 6 is increased to 16 volts and that R_L is increased to 2 kΩ. Draw the load line for these conditions on the characteristic curves shown below. Label the open circuit point A and the short circuit point B.

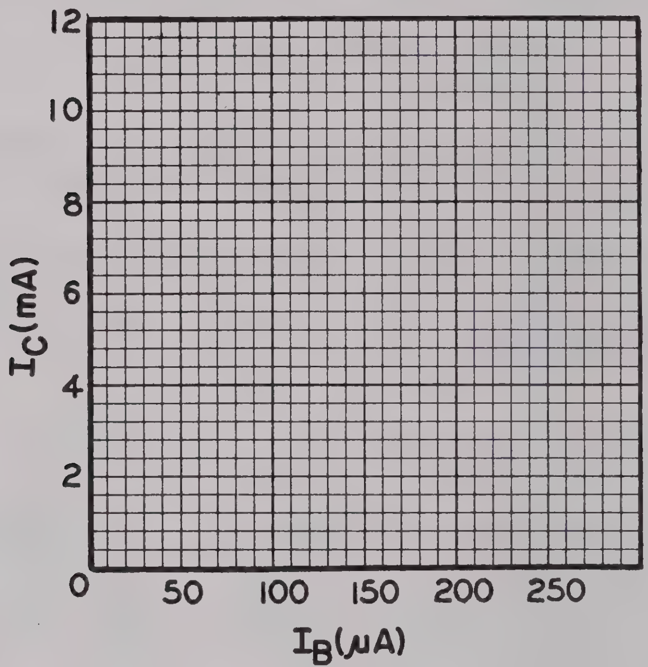


16. In a common-emitter amplifier such as the one shown in Figure 6, base current usually is larger than collector current. True or False?

17. What is the purpose of load resistor R_L of Figure 6?

18. Using the load line of Figure 8, if base current (I_B) changes from 50 μA to 150 μA, what is the change in collector current (I_C)?

19. Using the load line drawn for Practice Exercise 15, draw a transfer curve on the graph below.



20. The transfer characteristic curve of Figure 9 represents all values of load resistors R_L which can be put in a common-emitter circuit. True or False?

transistor that was used in the previous common-emitter explanations. Compare the labeling of these common-base characteristic curves and the common-emitter characteristic curves of Figures 3, 5, 7 and 8.

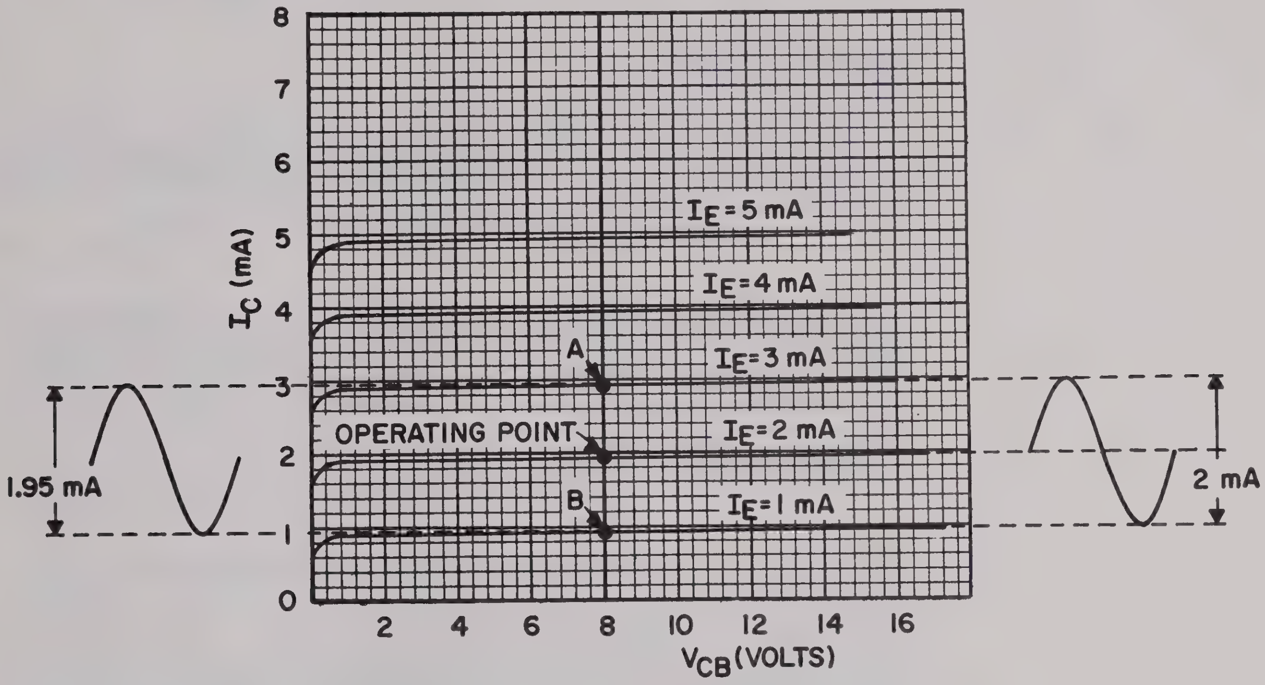


Figure 10

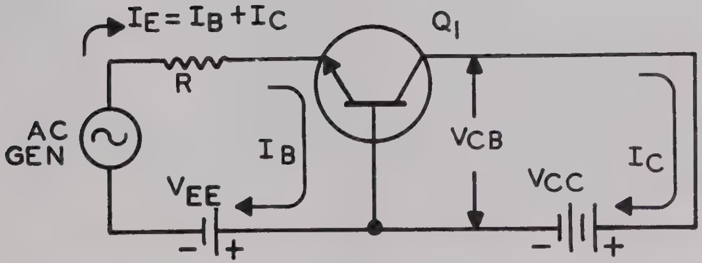


Figure 11

The collector current scales along the left side of the figures are similar. Though the scales are slightly different, collector current is measured in milliamperes in both types of figures. The scale at the bottom of Figure 10 shows collector-to-base voltage (V_{CB}). The curves in Figure 10 represent values of emitter current (I_E) in milliamperes, rather than base current values.

Current Gain h_{fb}

In a common-base transistor circuit such as that of Figure 11, emitter current (I_E) is the input current. The emitter current controls the flow of the circuit output current. The output current again is collector current (I_C).

The common-base characteristic curves are used in the same manner as the characteristic curves for a common-emitter circuit. Assume that V_{CC} of Figure 11 is an 8-volt battery. Since there is no load resistor in the circuit, the voltage from collector to base (V_{CB}) is always 8 volts in this circuit. On the curves of Figure 10, the solid line drawn vertically from the 8-volt point of the V_{CB} scale represents this condition.

Assume that V_{EE} causes 2 mA of emitter current (I_E) in the emitter circuit of Figure 11. This is represented in Figure 10 by the $I_E = 2$ mA curve. The point where the 8-volt V_{CB} line crosses the $I_E = 2$ mA curve is the operating point of the circuit of Figure 11. Assume that the generator which is in series with V_{EE} in the emitter circuit causes emitter current (I_E) to vary from 1 mA to 3 mA. This is a 2 mA peak-to-peak change about the operating point value of emitter current.

As before, when the input current changes, the collector current changes. In the case of the common-base circuit, the input current is emitter current I_E. The intersection of the $I_E = 3$ mA curve and the 8 volts V_{CB} line at point A gives a maximum value of approximately 3 mA for collector current. The intersection of the $I_E = 1$ mA curve and the 8-volt V_{CB} line at point B gives a minimum value of 1 mA for collector current. Thus, with an input current which changes 2 mA, the collector current changes approximately 2 mA (from 1 mA to 3 mA).

Current gain of a common-base amplifier is usually identified by the symbol $\mathbf{h}_{fb}$. The small b in the subscript indicates a common-base circuit. Current gain h_{fb} is equal to the change in collector current divided by the change in emitter current:

$$h_{fb} = \frac{\Delta I_C}{\Delta I_E} \tag{2}$$

As shown in Figure 10, when I_E in Figure 11 changes 2 mA, I_C changes 1.95 mA. Substituting these values into the equation:

$$h_{fb} = \frac{1.95\ \text{mA}}{2\ \text{mA}} = 0.975$$

The current gain does not quite equal 1, but in this case the current gain is so close to 1 that the difference cannot be seen from the graph. Current gain h_{fb} is sometimes indicated by the Greek letter **ALPHA (α)**.

The definition of h_{fb} is true only under the following conditions:

A CONSTANT COLLECTOR VOLTAGE IS USED IN DETERMINING h_{fb}. This is shown by the vertical line in Figure 10, which represents a constant collector voltage.

CHANGES IN EMITTER CURRENT MUST BE SMALL NEAR A GIVEN OPERATING POINT. Since the spacing between the characteristic curves varies, different values for h_{fb} could be arrived at by comparing large changes in base current. This could result in false values for h_{fb}.

THE h_{fb} OF A GIVEN TRANSISTOR TYPE IS ONLY A TYPICAL OR AVERAGE VALUE. Therefore, the h_{fb} of a given transistor may range above or below this average value. Manufacturers often indicate how far above or below this average value the actual h_{fb} of their transistors may range.

Under the conditions stated above, THE CURRENT GAIN, h_{fb}, OF A COMMON-BASE AMPLIFIER USING A BIPOLAR JUNCTION TRANSISTOR IS ALWAYS LESS THAN 1. Therefore, in Equation 2, ΔI_C is always less than ΔI_E. What, then, is the advantage of a common-base amplifier? The common-base amplifier is capable of producing a relatively large output voltage change when the input current change is small. This is true, of course, only when a load resistor is used in the collector circuit. Collector current, which is nearly equal to emitter current, causes a large voltage to be developed across the large resistance of the collector load resistor.

Load Lines

The output voltage of the common-base circuit of Figure 12 is developed by load resistor R_L. Collector current, passing through R_L, produces an output voltage which is proportional to the collector current. To see how the circuit works, a load line that represents this resistor will be constructed on characteristic curves. Assume that R_L has a value of 1000 ohms and that R_1 is 200 ohms. The load line drawn on the characteristic curve of Figure 13 represents load resistor R_L in the circuit of Figure 12, where V_{CC} is 8 volts. Let V_{EE} be 1.6 volts. Construction procedure for this load line is very similar to that explained for the common-emitter circuit.

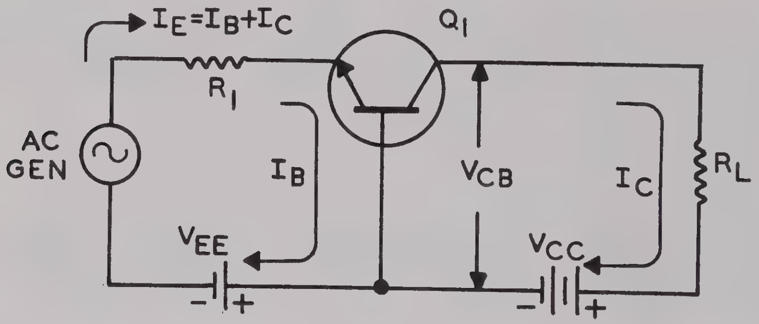


Figure 12

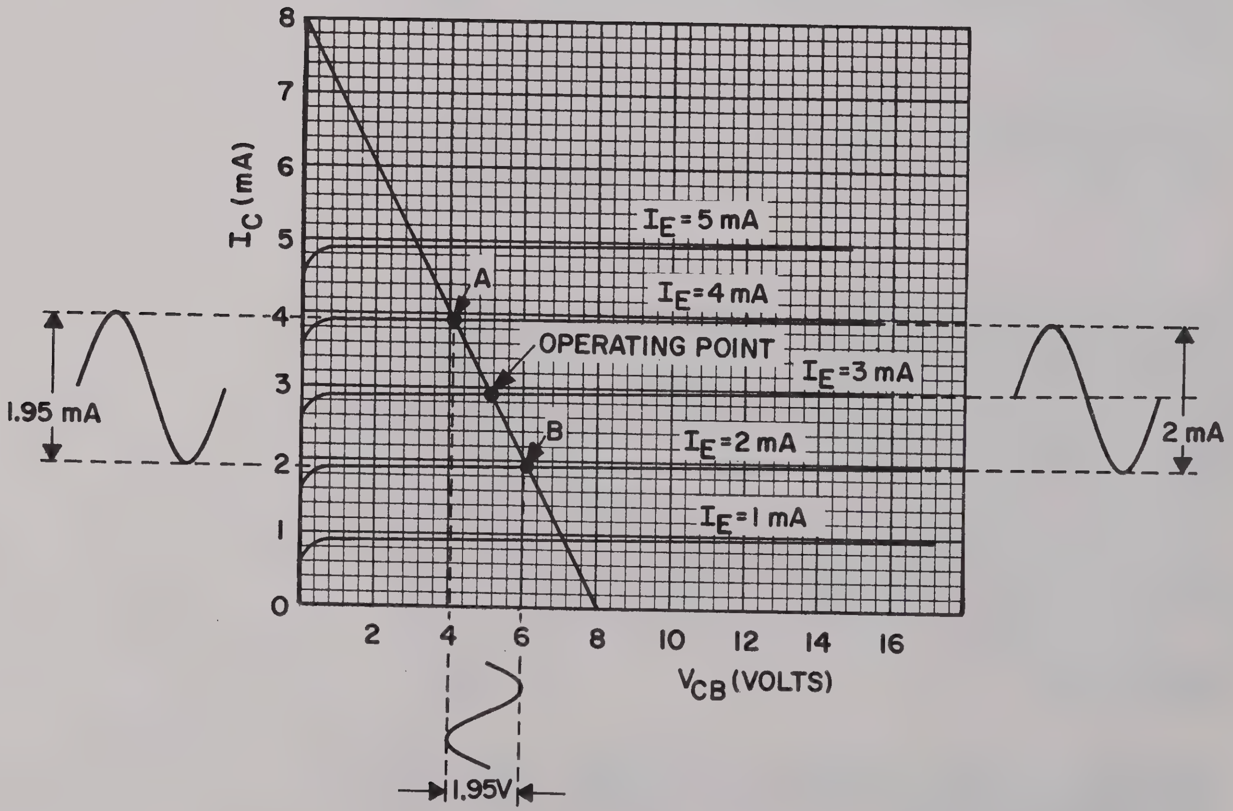


Figure 13

The open circuit point for the load line is equal to the collector supply voltage, V_{CC}, with I_C equal to zero. The short circuit point must include both the value of R_1 in the emitter circuit, and the value of R_L. In addition, the values of both V_{EE} and V_{CC} must be used to determine the maximum collector current. The maximum value of collector current, with the collector-to-emitter voltage equal to zero, is equal to:

$$\frac{V_{EE} + V_{CC}}{R_1 + R_L}$$

Substituting the values given above into this expression gives:

$$\frac{V_{EE} + V_{CC}}{R_1 + R_L}$$

$$= \frac{1.6 + 8}{200 + 1000}$$

$$= \frac{9.6}{1200}$$

$$= .008\text{A, or } 8 \text{ mA,}$$

for the short circuit current.

To illustrate the use of the common-base curves, assume that emitter current I_E is 3 mA. The intersection of the $I_E = 3$ mA curve and the load line is now the operating point. Suppose that the ac generator causes a change of 2 mA peak-to-peak in the emitter current of Figure 12. As shown on the characteristic curves of Figure 13, emitter current varies from 2 mA to 4 mA. This causes collector current I_C to vary from about 1.95 mA to 3.9 mA, for a total change of 1.95 mA, as shown at the left of the figure. Thus, the change of input current (I_E) of 2 mA causes a change in output current (I_C) of 1.95 mA.

Output voltage can be computed using Ohm's Law as explained for the common-emitter amplifier. In Figure 12, the change in amplitude of output voltage across R_L is the same as the change in amplitude of voltage from collector to base. This collector-to-base voltage change can be read directly from the curves of Figure 13. Follow the dashed lines from points A and B down to the V_{CB} scale. Points A and B correspond to V_{CB} values of 4.1 volts and 6.05 volts, respectively. This means that the collector-to-base voltage, V_{CB}, changes 1.95 volts peak-to-peak.

As mentioned previously, the common-base circuit is useful because it is capable of producing a relatively large output voltage change across a load resistor. By using different values of load resistor R_L, different output voltage changes can be obtained. In this instance, with a 1000-ohm load, a 2-mA input current change causes an output voltage change of 1.95 volts.

The characteristic curves of Figures 10 and 13 give the same information for a common-base circuit as the previous curves did for a common-emitter circuit. If required, a transfer curve can be constructed from these collector characteristics in much the same manner as described for the common-emitter circuit.

TRANSISTORS AND POWER

Characteristic curves tell you what to expect from a transistor that is working within its normal range. It is also important to know what things limit transistor operation. If certain values of current, voltage or power are exceeded, the transistor no longer works properly. These values are called maximum transistor ratings. They are listed on manufacturers' data sheets as well as in transistor manuals.

Maximum Transistor Ratings

One very important rating is the maximum power-handling ability of a transistor. This rating is usually given on a data sheet as maximum power dissipation or maximum collector dissipation. Depending on the type of transistor, this power rating varies from a fraction of a watt to many watts. A transistor used in a portable transistor radio will usually have a power rating measured in milliwatts, while transistors used in power supplies and power amplifiers have ratings up to several hundred watts.

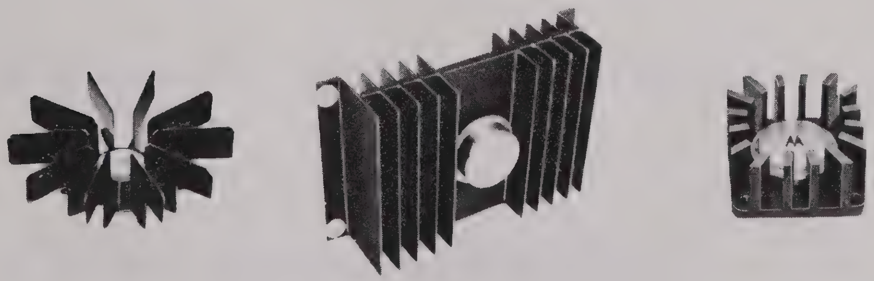
A transistor dissipates power in the form of heat. Excessive heat damages a transistor. Power is the rate at which energy is developed or used. Heat is a form of energy. Thus, it follows that a greater dissipation of power means a greater amount of heat. In transistors, as in other electronic devices, some electrical power is always converted into heat energy.

The majority of the heat in a transistor is developed in the collector-base junction. When the maximum power rating of the transistor is exceeded, too much heat develops at this junction. This heat may cause the materials which form the junction to actually melt or break down. The resistance of the collector-base junction of a transistor under normal operating conditions is large. As the temperature of the junction increases, the resistance of the junction decreases. If the materials which form the junction become hot enough to melt, the transistor no longer works properly and is permanently damaged.

On a data sheet you will also find a maximum collector current rating. If a current larger than this value is allowed in the collector circuit, the maximum power rating of the transistor may be exceeded. As explained previously, this could result in a damaged transistor.

Another important rating is the maximum collector voltage. A transistor is usually damaged in a slightly different way when the maximum collector voltage is exceeded. Current may flow through the transistor in channels. That is, more current crosses the collector-base junction at one point than at another. This causes the collector-base junction to heat up more at one point than at another. If the current is great enough at the one point, the junction materials at that point will melt. This results in a low-resistance path for current across the collector-base junction. This path will now remain, even after the voltage is removed. The transistor no longer can work correctly.

These maximum ratings, as given on data sheets, are for a given surrounding or ambient temperature. This temperature is usually 25°C, which is equal to 77°F. If the ambient temperature is higher than this value, the transistor's maximum ratings must be lowered. That is, as the temperature of a transistor's surroundings increases, the transistor can handle less power. The opposite is also true, and a transistor operating below the specified ambient temperature can handle more power. Heat sinks are often used to help dissipate heat from a transistor.



The photo above shows several different types of heat sinks. Heat sinks such as these increase the power-handling capabilities of a transistor.
Courtesy Wakefield Engineering, Inc.

SUMMARY

A characteristic curve is a graph or picture of the variations of currents and voltages in a transistor. The most commonly used characteristic curves are the collector characteristic curves. They are used when the transistor is connected in a common-emitter circuit. The common-base curves are used when the transistor is connected in a common-base circuit.

The load line drawn on the characteristic curves represents all of the possible operating conditions with a given load resistor in the circuit. If the input signal current is known, the output signal current can be found by use of the curves and the load line.

A transfer characteristic curve is constructed from the collector characteristic curves. It shows how output current varies with respect to input current. A transfer characteristic curve represents only one value of supply voltage and load resistor. If the supply voltage or the load resistor of the circuit is changed, a new transfer characteristic curve must be drawn.

The maximum ratings of a transistor are values which should not be exceeded. Permanent damage can occur if some of the maximum values are ignored. Examples of maximum transistor ratings are: maximum collector current, maximum collector voltage, maximum power and maximum operating temperature.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

COMMON-BASE CIRCUITS

CHARACTERISTIC CURVES

CURRENT GAIN h_{fb}

LOAD LINES

TRANSISTORS AND POWER

MAXIMUM TRANSISTOR RATINGS

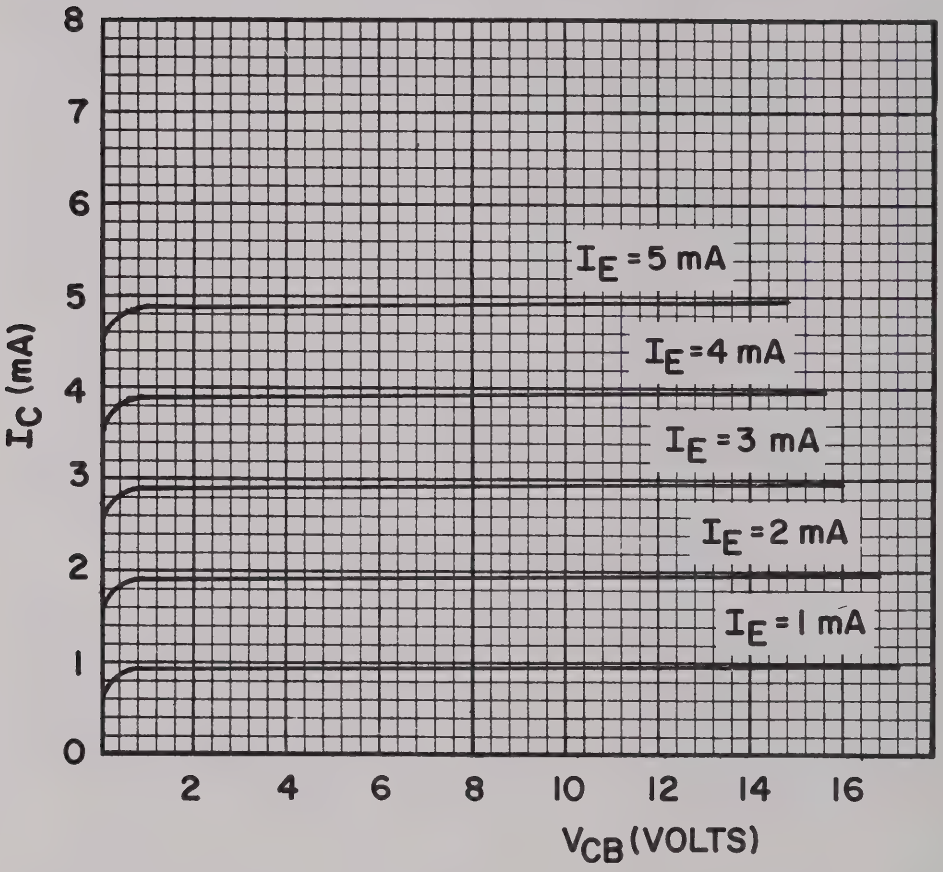
21. The term h_{fb} represents the current gain of a (a) common-emitter transistor amplifier, (b) common-base transistor amplifier.

22. In Figure 10, if V_{CB} is 14 volts and I_E is 4 mA, what is I_C?

23. Can ΔI_C ever be greater than ΔI_E? If not, why not?

24. The characteristic curves of Figures 10 and 13 are for ______________ ____________ amplifiers.

25. In the figure below, draw a load line for V_{CC} of 12 volts, R_1 of 200 ohms, R_L of 1800 ohms and V_{EE} of 2 volts.



26. Excessive collector current or voltage can damage a transistor. True or False?

27. The purpose of a heat sink is to (a) heat a transistor, (b) cool a transistor.

28. Is it heat that actually damages a transistor?

IMPORTANT DEFINITIONS

ALPHA (α) (h_{fb}) — A common method of denoting the current gain for a common-base transistor amplifier circuit.

BETA (β) (h_{fe}) — A common method of denoting the current gain for a common-emitter transistor amplifier circuit.

CHARACTERISTIC CURVE — A graphic representation of the changes that occur in a circuit under given conditions. For example, the nature of the output current change of a transistor with a change in the input current.

COLLECTOR CHARACTERISTIC CURVE — A characteristic curve that shows how collector current varies with changes in base current and collector-to-emitter voltage.

CURRENT GAIN — The ratio or output current change to input current change.

LOAD LINES — Lines representing given load resistors, drawn across a set of characteristic curves to show voltage and current changes in a particular circuit.

OPERATING POINT — The point on a transistor characteristic graph which represents the values of base current (I_B) and collector current (I_C) with no signal applied.

TRANSFER CHARACTERISTIC CURVE — A curve that shows how the voltage or current of one electrode affects the voltage or current of another electrode with a given value of load resistance.

ESSENTIAL SYMBOLS AND EQUATIONS

V_{CE}	Collector-to-emitter voltage
V_{CB}	Collector-to-base voltage
I_C	Collector current
I_B	Base current
I_E	Emitter current
V_{BB}	Base supply voltage
V_{CC}	Collector supply voltage
V_{EE}	Emitter supply voltage
Δ	A small change

$$h_{fe} = \frac{\Delta I_C}{\Delta I_B} \tag{1}$$

$$h_{fb} = \frac{\Delta I_C}{\Delta I_E} \tag{2}$$

PRACTICE EXERCISE SOLUTIONS

1. **Collector current is directly proportional to base current. Increasing base current increases collector current, and vice versa. Beyond a small value of collector-to-emitter voltage, collector current is relatively constant.**

2. **The greatest change in collector current occurs below a V_{CE} of about 2 volts. Above 2 volts, I_C remains relatively constant.**

3. **The graph of Figure 3 is referred to as a family of characteristic curves which show how the collector current varies with changes in the base current and the collector-to-emitter voltage.**

4. **10 mA. — The lines which represent a collector-to-emitter voltage, V_{CE}, of 8 volts and the 200 μA characteristic curve intersect at point B. The value of collector current at point B is 10 milliamperes.**

5. **250 μA. — The line which represents a collector current I_C of 12.4 milliamperes and the line which represents a collector-to-emitter voltage of 8 volts intersect at point C. Point C lies on the base current curve labeled 250 microamperes.**

6. **(a) common-emitter circuit.**

7. **True**

8. **h_{fe} equals a change in collector current divided by a change in base current with the collector voltage held constant.**

9. **5.6 mA. — Collector current changes from 2 mA to 7.6 mA.**

10. **56. —** $\frac{(7.6\ \text{mA} - 2\ \text{mA})}{100\ \mu\text{A}} = \frac{(7600\ \mu\text{A} - 2000\ \mu\text{A})}{100\ \mu\text{A}} = \frac{5600}{100} = 56.$

11. **False — The slope of the load line depends upon the value of the load resistor.**

12. **True — The larger the resistance of the load, the less the slope of the load line.**

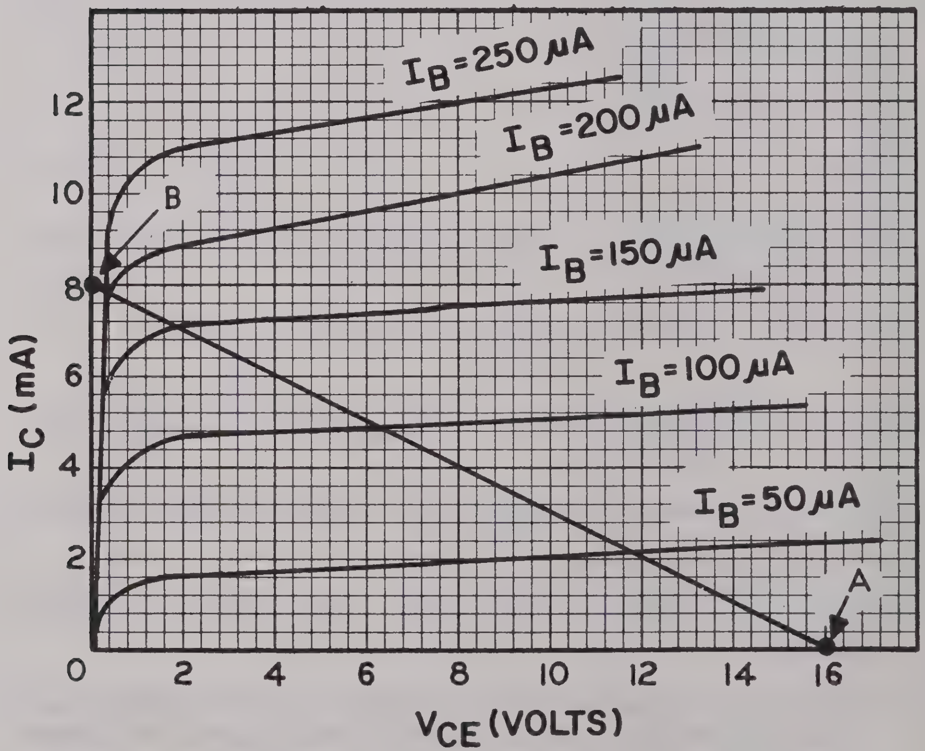
13. **The open circuit point is found by letting the collector current equal zero. The collector-to-emitter voltage is therefore equal to the collector supply voltage. The short circuit point is found by letting the collector-to-emitter voltage equal zero. The resultant collector current is equal to the value of collector supply voltage divided by the collector load resistance.**

PRACTICE EXERCISE SOLUTIONS (Continued)

14. If the short circuit point cannot be plotted on the characteristic curves, pick a value of collector current less than the short circuit value that can be plotted on the curves. Using this value of collector current, determine the voltage drop across the load resistor and then the collector-to-emitter voltage. The resultant collector-to-emitter voltage and collector current form the second point for the load line.

15. To draw the load line, first determine the open circuit point, which is equal to an I_C value of 0 and a V_{CE} value equal to the collector supply, V_{CC}, 16 volts. This is shown as point A on the characteristic curves below.

    The short circuit point, with V_{CE} equal to zero, is found by dividing the value of V_{CC} by R_L, 16 volts ÷ 2 kΩ = 8 mA. Since this point can be plotted on the curve, it can be used as point B on the curves below. The load line is then drawn between points A and B, as shown.



16. False — The collector current is usually larger than the base current.

PRACTICE EXERCISE SOLUTIONS (Continued)

17. Load resistor R_L develops the output voltage of the circuit and limits I_C to a safe value.

18. 5.2 mA. — Collector current I_C changes approximately from 2 mA to 7.2 mA.

19. The following points for the transfer characteristic curve are taken from the load line drawn in Practice Exercise 15:

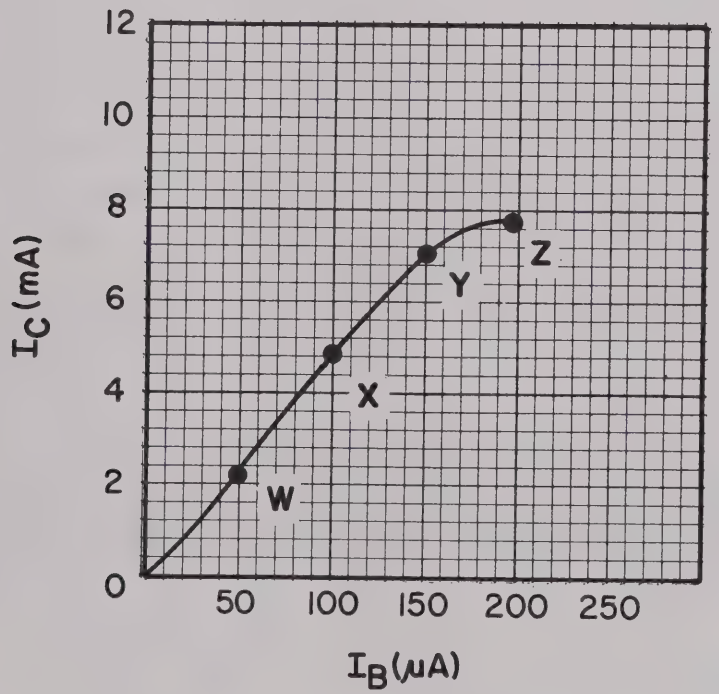
W: $I_B = 50\ \mu A$, $I_C = 2.2$ mA.

X: $I_B = 100\ \mu A$, $I_C = 4.9$ mA.

Y: $I_B = 150\ \mu A$, $I_C = 7$ mA.

Z: $I_B = 200\ \mu A$, $I_C = 7.8$ mA.

Points W, X, Y and Z are plotted on the graph below and a smooth line is drawn between them to form the transfer curve.



20. False — For every different load resistor and value of V_{CC}, a different transfer curve must be constructed.

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ONE OF THE
BELL & HOWELL SCHOOLS

1046A & B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

1046B

1. C - THE CURVES OF FIGURE 3 ARE -- COMMON EMITTER CHARACTERISTIC CURVES.
The common emitter curves show how collector current varies with changes in base current and collector-to-emitter voltage.

2. C - THE CURVES OF FIGURE 3 SHOW THAT WITH A GIVEN COLLECTOR-TO-EMITTER VOLTAGE, -- I_C INCREASES WHEN I_B INCREASES.
Collector current in a transistor is directly proportional to base current. Increasing base current increases collector current and vice versa.

3. C - IN A COMMON-EMITTER AMPLIFIER WITH CONSTANT COLLECTOR VOLTAGE, IF THE CHANGE IN I_C IS 10 mA AND THE CHANGE IN I_B IS 200 µA, h_{fe} EQUALS -- 50.
The common emitter current gain, h_{fe}, is equal to the change in collector current divided by the change in base current. In this case h_{fe} is equal to 10,000 µA ÷ 200 µA or 50.

4. C - IF THE VALUE OF R_L IN FIGURE 6 IS INCREASED TO 1,000 OHMS, -- THE VALUE OF SHORT CIRCUIT CURRENT WILL DECREASE.
The value of short circuit current, $V_{CE} = 0$, is equal to the collector supply voltage divided by the load resistance. Increasing the value of R_L decreases the short circuit current, and vice versa. The value of R_L has no effect on the open circuit point. It is determined solely by the value of the collector supply voltage.

5. D - THE CURRENT GAIN (h_{fe}) OF A COMMON-EMITTER CIRCUIT IS USUALLY -- LARGER THAN THE CURRENT GAIN h_{fb}.
The current gain h_{fb} of a common base circuit is always less than one. The current gain h_{fe} of the common emitter stage is much greater than one. Values of h_{fe} as high as 400 are not uncommon.

6. D - WITH A GIVEN VALUE OF I_B IN THE COMMON EMITTER CIRCUIT, -- I_C IS RELATIVELY CONSTANT AS V_{CE} IS VARIED.
The transistor is a constant current device. Beyond a certain value of V_{CE}, I_C remains relatively constant as V_{CE} is varied.

7. D - IN A COMMON BASE CIRCUIT SUCH AS THAT SHOWN IN FIGURE 12, -- I_E CONTROLS I_C.
In the common base circuit, the emitter current I_E is the input current and it controls collector current I_C. The output current I_C in a common base circuit is always less than the input current I_E.

8. A - THE LINE DRAWN THROUGH POINTS C AND D OF FIGURE 8 IS A -- LOAD LINE.
The load line shows how collector current and collector voltage vary with base current for a given value of load resistance.

9. D - THE SLANT OR SLOPE OF A LOAD LINE DEPENDS UPON -- THE RESISTANCE OF THE LOAD RESISTOR.
As the value of load resistance is decreased, the slope of the load line increases. In Figure 7, line 1 represents a low value of load resistance while line 4 represents a high value of load resistance.

10. D - THE CURVE OF FIGURE 9 IS A -- TRANSFER CHARACTERISTIC CURVE.
The transfer characteristic curve is derived from the collector characteristic curves and the load line. It shows the operation of the transistor with a given value of load resistance.

1046A

All explanations are the same as for 1046B except for those given below.

7. D - IN A COMMON BASE CIRCUIT SUCH AS FIGURE 13, -- I_E CONTROLS I_C.
In the common base circuit, the emitter current I_E is the input current and it controls collector current I_C. The output current I_C in a common base circuit is always less than the input current I_E.

9. D - THE SLANT OR SLOPE OF A LOAD LINE DEPENDS UPON -- THE SIZE OF THE LOAD RESISTOR.
As the value of load resistance is decreased, the slope of the load line increases. In Figure 7, line 1 represents a low value of load resistance while line 4 represents a high value of load resistance.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1046B

Example: A ☐ B ☐ C ☐ D ■ A member of the cat family is the

A. baboon. B. elephant. C. hippopotamus. D. lion.

1. A ☐ B ☐ C ☒ D ☐ **The curves of Figure 3 are**
(A) common-base characteristic curves. (B) transfer characteristic curves. (C) common-emitter characteristic curves. (D) load lines.

2. A ☐ B ☐ C ☒ D ☐ **The curves of Figure 3 show that, with a given collector-to-emitter voltage,**
(A) I_C decreases when I_B increases. (B) I_E decreases when I_C increases. (C) I_C increases when I_B increases. (D) I_C is independent of I_B.

3. A ☐ B ☐ C ☒ D ☐ **In a common-emitter amplifier with constant collector voltage, if the change in I_C is 10 mA and the change in I_B is 200 μA, h_{fe} equals**
(A) 25. (B) 10. (C) 50. (D) 100.

4. A ☐ B ☐ C ☒ D ☐ **If the value of R_L in Figure 6 is increased to 1000 ohms,**
(A) the open circuit point for the load line will move to the left. (B) the open circuit point for the load line will move to the right. (C) the value of short circuit current will decrease. (D) the value of short circuit current will increase.

5. A ☐ B ☐ C ☐ D ☒ **The current gain (h_{fe}) of a COMMON-EMITTER circuit is usually**
(A) equal to a change in I_C divided by a change in I_E. (B) smaller than the current gain, h_{fb}. (C) equal to the current gain, h_{fb}. (D) larger than the current gain, h_{fb}.

6. A ☐ B ☐ C ☐ D ☒ **With a given value of I_B in the common-emitter circuit,**
(A) I_C decreases as V_{CE} increases. (B) I_C increases greatly as V_{CE} increases. (C) I_B has no control over I_C. (D) I_C is relatively constant as V_{CE} is varied.

7. A ☐ B ☐ C ☐ D ☒ **In a common-base circuit such as that shown in Figure 12,**
(A) I_E has no effect on I_C. (B) I_C controls I_E. (C) I_C is larger than I_E. (D) I_E controls I_C.

8. A ☒ B ☐ C ☐ D ☐ **The line drawn through points C and D of Figure 8 is a**
(A) load line. (B) transfer characteristic curve. (C) common-emitter collector characteristic curve. (D) common-base collector characteristic curve.

9. A ☐ B ☐ C ☐ D ☒ **The slant or slope of a load line depends upon**
(A) the kind of transistor. (B) the size of the collector supply. (C) the size of the input signal. (D) the resistance of the load resistor.

10. A ☐ B ☐ C ☐ D ☒ **The curve of Figure 9 is a**
(A) load line. (B) common-base collector characteristic curve. (C) common-emitter collector characteristic curve. (D) transfer characteristic curve.

EXPERIMENT 2

TRANSISTOR CIRCUITS - DC CHARACTERISTICS OF NPN AND PNP TRANSISTORS

PARTS NEEDED

1 - Multimeter with Test Leads and Spring Adapters
1 - Partially Completed Design Console
1 - NPN Transistor
1 - PNP Transistor
12 - Modular Connectors
2 - 10 kΩ, 1/2 W, 20% Resistors
1 - 470 kΩ, 1/2 W, Resistor
1 - 1 MΩ, 1/2 W, 20% Resistor
1 - 5 kΩ Potentiometer with Mounting Bracket
1 - Silicon Diode
1 - 10 μF, 50 Volt, Electrolytic Capacitor
1 - Transistor Socket with Leads
- No. 22 Solid Hookup Wire
2 - Tri-mounts

OBJECTIVE

In this experiment, you will investigate the basic dc action of NPN and PNP transistors. The tests will show how collector current and the voltage at the collector vary with changes in base current.

PART 1

PROCEDURE

NPN TRANSISTOR CHARACTERISTICS

1. Connect the circuit of Figure 2-1, following the layout shown in Figure 2-2. Make sure that the design console is turned off while you set up or change the circuit. Fasten the 5 kΩ potentiometer, R_2, to the modular panels by placing the tri-mounts in the holes in the bracket and pushing them into holes on the design panels. Remember that part of connecting the circuit is the installation of all tubes and transistors. In this circuit an NPN transistor is used.

The rectifier circuit consisting of D_1, C_1, and R_2 is used to develop a bias voltage for Q_1. By varying R_2, the bias on Q_1 can be changed; and the corresponding changes in base and collector current, as well as collector voltage, can be observed. Rotating the R_2 shaft clockwise increases the voltage across R_3 and this increases the current through R_3. This current is also the Q_1 base current. In Figure 2-1, the "CW" and the upward pointing arrow by R_2 indicate that physically rotating the R_2 shaft clockwise is the same as raising the slider of R_2 on the schematic, Figure 2-1.

2. Set the shaft on R_2 fully counterclockwise. This sets the base current at minimum or zero. Rotate the Adjust Voltage control to its fully counterclockwise

position. Turn on the design console by setting the switch to the 30V position. Connect your multimeter to measure the supply voltage, and set it at 15 volts.

3. To measure base current, merely measure the voltage from the slider of R_2 to ground (GND); and divide this voltage by the rated value of R_3, 1 MΩ. Assume the measured voltage to be the voltage across R_3. For example, suppose that you measure 2 volts; the approximate base current is then:

$$I_B = \frac{E_{R_3}}{R_3} = \frac{2 \text{ volts}}{1 \text{ M}\Omega} = \frac{2}{1 \times 10^6} = 2 \times 10^{-6}\text{A (or } 2\ \mu\text{A).}$$

4. With R_2 set fully counterclockwise, measure the voltage at the slider of R_2, point X, in Figure 2-2 and compute the base current, I_B. Remember, all of the voltage measurements are to be made with respect to ground. With the shaft on R_2 fully counterclockwise, you should not measure any voltage from the slider of the potentiometer to ground. Then there is also no voltage across R_3, which means that there is no current in R_3 or in the base of Q_1. You will find a 0 entered in the column for I_B in the first row (for $E_{R_3} = 0$ volts). Next, measure the voltage at the collector (V_C); it should be very close to 15 volts (therefore "15V" was entered in the next space to the right under "V_C"). In this part of the experiment, the supply voltage is +15 volts. To find I_C (for the last column in Figure 2-3), the voltage drop for R_1 is needed first:

$$E_{R_1} = 15 - V_C.$$

Since $V_C = 15$ volts (for the row in Figure 2-3 where $E_{R_3} = 0$), $E_{R_1} = 15 - 15 = 0$ volts.

The voltage across R_1 is zero, thus the current through R_1 is zero also, as you will see entered in the last space (under I_C) in the row for $E_{R_3} = 0$ volts.

The next set of readings will be for the next row (of $E_{R_3} = 2$V). Rotate the slider of R_2 clockwise until you measure 2 volts from the slider to ground. Assuming that this 2 volts also appears across R_3 (the 1 MΩ resistor), the current has been determined by the equation in the previous step: 2 µA, which you will find entered under I_B. At the collector of Q_1, your multimeter should now indicate a voltage a little less than 15 volts. Record the reading in the "V_C" column. To find I_C for this row, subtract your reading for V_C from 15 volts to find the drop across R_1. Then the drop across R_1 is divided by 10 kΩ, the rated resistance of R_1. For example, if V_C was 13.5 volts, the drop across R_1 was 1.5 volts, and the current through R_1 was then 1.5 volts divided by 10 kΩ giving 0.15 mA (or 150 µA). "13.5V" would be entered in the V_C column and "0.15 mA" would be entered under "I_C."

The third row for readings is for E_{R_3} equal to 4 volts. Rotate the shaft of R_2 clockwise again until the voltage at the slider is 4 volts above ground. The base current, I_B, is the voltage drop of R_3 (4 volts) divided by the resistance, 1 MΩ (to give 4 μA which is recorded in Figure 2-3). The V_C is again found at the collector and also entered in Figure 2-3. Then I_C is equal to 15 - V_C divided by 10 kΩ. I_C is then recorded in the Figure.

5. Complete the chart of Figure 2-3 by setting R_2 for each of the voltages indicated as E_{R_3}. Measure the voltage at the collector, and compute the base and collector currents for each value of E_{R_3}. Begin with $E_{R_3} = 2V$.

6. The characteristics of a device are easily observed if the data is converted into a graph. Using the values for I_B and I_C in the chart of Figure 2-3, plot the curve of I_C versus I_B on the graph of Figure 2-4. Locate each value of I_B, and mark the corresponding value of I_C with a dot. After you have located each point, connect them with a smooth line. Your characteristic curve should look something like the example of Figure 2-5.

Since individual transistors with the same transistor number differ, each transistor will have a different curve. When manufacturers publish data, they are "average" (typical) characteristics which are derived by measuring the characteristics of many devices and averaging the characteristics.

7. The data in the chart of Figure 2-3 can be used to calculate the current gain (or Beta, β) of the transistor. Current gain is found by dividing a change in collector current by the change in base current. Transfer the collector current values from the chart of Figure 2-3 for base currents of 4 μA and 6 μA to the places provided below.

$I_B = 4\ \mu A$ $I_C =$ 200 μA

$I_B = 6\ \mu A$ $I_C =$ 450 μA

8. Now determine the changes of base current and collector current, by subtracting the smaller value from the larger. The change in base current will be 6 μA - 4 μA or 2 μA. Enter values below.

Base Current Change $\Delta I_B = 2\ \mu A$

Collector Current Change $\Delta I_C =$ 250 μA

9. Compute the current gain by dividing the change in I_C by the change in I_B and enter below.

$$\text{Current Gain} = \frac{\Delta I_C}{\Delta I_B} = \frac{250}{2} = 125$$

Current gain (or β) is a pure number (a ratio), and your computed value should be 50 or more for the NPN transistor.

CONCLUSION

The data recorded in Figure 2-3 and plotted in Figure 2-4 shows that collector current is directly proportional to base current. In addition, the chart of Figure 2-3 shows that collector voltage is inversely proportional to base current and collector current. You were able to calculate the β (or current gain) by dividing a change in collector current by a corresponding change in base current.

PART 2

PROCEDURE

PNP TRANSISTOR CHARACTERISTICS

1. Connect the circuit of Figure 2-6 following the layout shown in Figure 2-7. Substitute the PNP transistor for the NPN transistor used in the previous steps. Make sure that the design console is turned off while constructing the circuit. This circuit is essentially the same as that for the NPN circuit of Figure 2-1. The major difference is the opposite supply polarity.

2. Set the shaft on R_2 fully counterclockwise. This sets the base current at minimum. After rotating the Adjust Voltage control fully counterclockwise, turn the selector switch to the 30 volt position. Connect your multimeter to measure the supply voltage, and set it at 15 volts. Remember, all dc voltages are negative with respect to ground in this PNP circuit.

3. Base current and collector current are measured in the same manner as for the previous circuit. However, note that the value of R_3 is 470 kΩ in this circuit. For your calculations, use a value of 500 kΩ for R_3. This will simplify the calculations and not introduce any appreciable error.

4. Complete the chart of Figure 2-8 by setting R_2 for the indicated voltages. The voltage at the slider of R_2 is measured at point X in the layout of Figure 2-7.

5. Now, using the data from the chart of Figure 2-8, construct a graph showing how I_C varies with I_B on the graph of Figure 2-9. Note that the values of I_C and I_B are shown as negative, since we are dealing with a PNP transistor. You may notice that the leakage of germanium transistors is greater than that of silicon transistors.

6. Calculate the current gain of the transistor by using the same technique as for the NPN circuit. Use base current values of 12 μA and 16 μA to determine the change in collector current. Enter your computed β below.

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{200\mu}{4\mu} = 50$$

CONCLUSION

As in the NPN circuit, collector current is directly proportional to base current in the PNP circuit. Likewise, collector voltage is inversely proportional to base current and collector current. The computed β (or current gain) of the PNP transistor should also be greater than 25.

NOTES

$\frac{25}{10} \times .25A$

12.5

.25A

4.5

4.5

.5

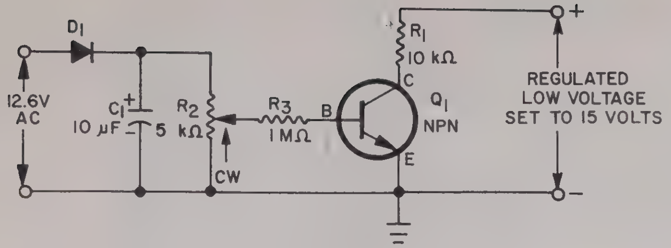

FIGURE 2-1

E_{R3}	I_B	V_C	I_C
0V	0 μA	15 V	0 mA
2V	2 μA	14	.1m
4V	4μ	12	.2
6V	[illegible]	9.5	.45
8V	[illegible]	7	.8
10V	[illegible]	4	1.1
12V	[illegible]	1.5	1.35
14V	[illegible]	.5	1.45

FIGURE 2-3

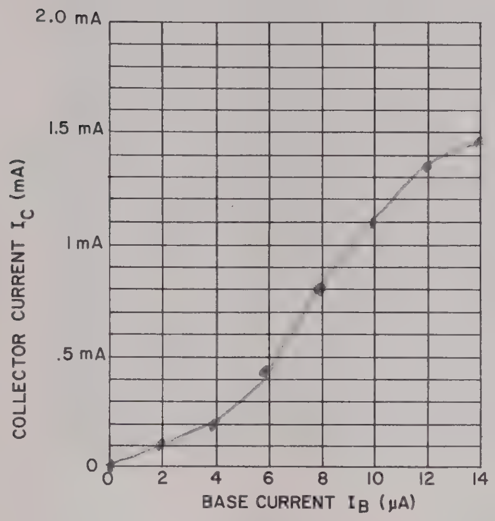

FIGURE 2-4

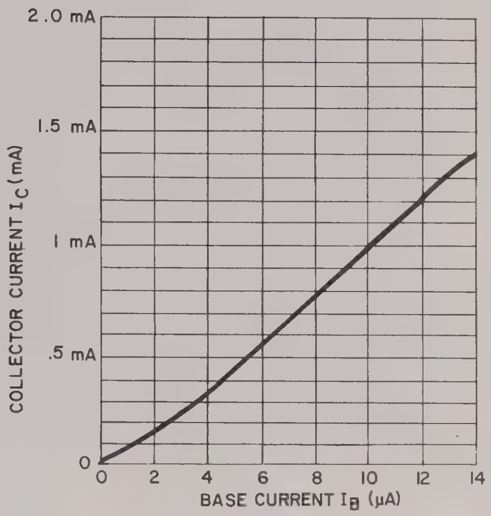

FIGURE 2-5

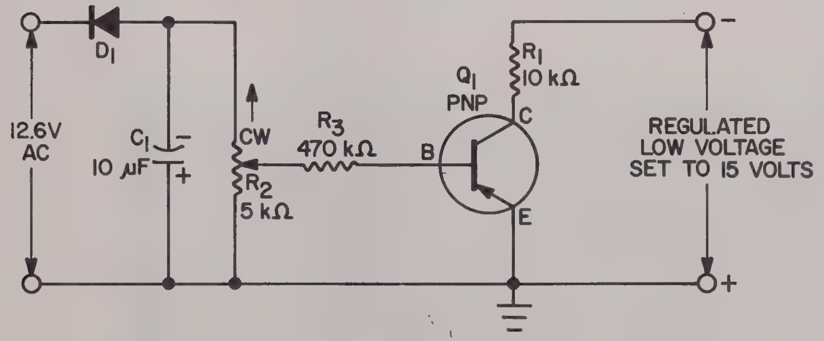

FIGURE 2-6

E_{R3}	I_B	V_C	I_C
0V	0 μA	14 V	.1 mA
2V	4μ	9.5	.45
4V	8μ	7	.8
6V	12μ	4	1.1
8V	16μ	2	1.3
10V	20μ	.5	1.45
12V	24μ	0	1.5
14V	28μ	0	1.5
16V	[illegible]	0	1.5

FIGURE 2-8

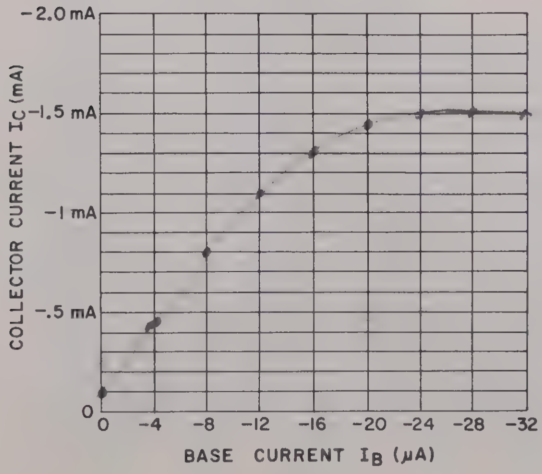

FIGURE 2-9

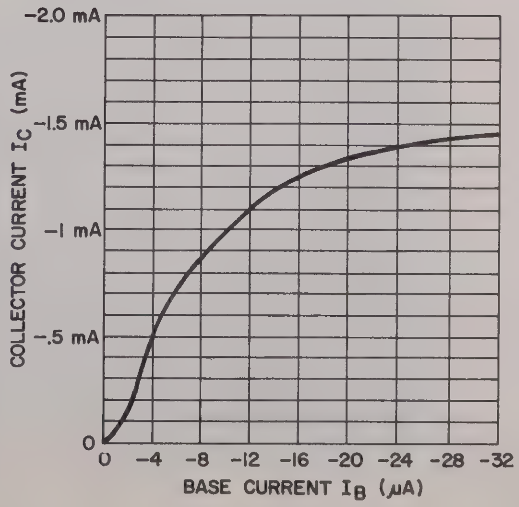

FIGURE 2-10

NOTES

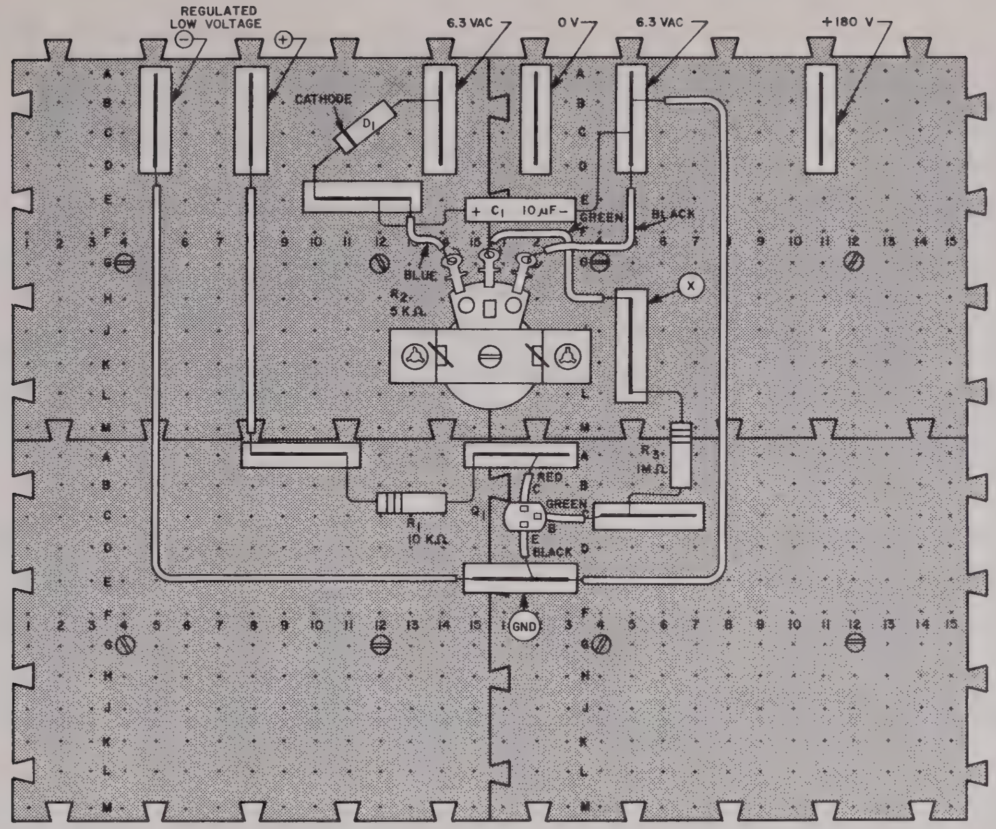

FIGURE 2-2

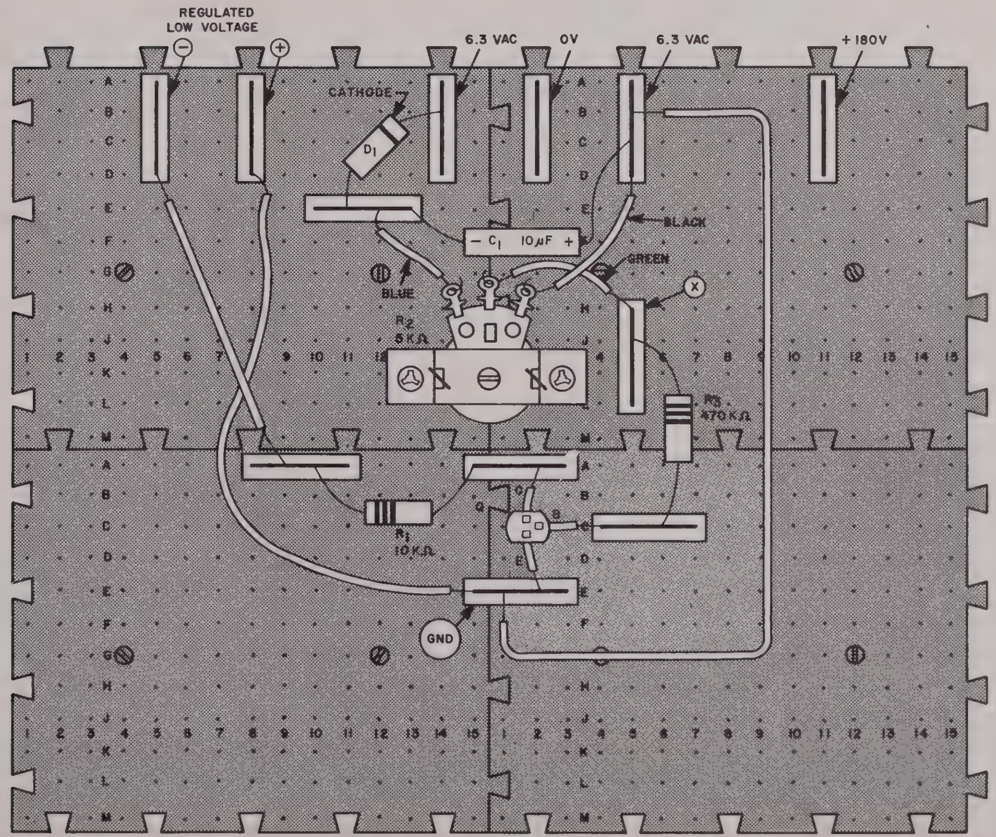

FIGURE 2-7

NOTES

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4141 BELMONT AVENUE, CHICAGO, ILLINOIS 60641

ONE OF THE
BELL & HOWELL SCHOOLS

9504-2A
EXAMINATION CHECK SHEET

1. A - IN A TRANSISTOR, COLLECTOR CURRENT IS -- DIRECTLY PROPORTIONAL TO BASE CURRENT.
In a transistor, collector current is controlled by base current. As the base current is increased, collector current increases. Reducing base current causes collector current to decrease.

2. B - IN THE CIRCUIT OF FIGURE 2-1, WHEN BASE CURRENT DECREASES, -- COLLECTOR VOLTAGE INCREASES.
A decrease in base current decreases collector current, reducing the voltage drop across the collector load resistor, thereby increasing the collector voltage.

3. B - WHICH OF THE FOLLOWING FORMULAS DESCRIBES THE CURRENT GAIN OF A TRANSISTOR?

-- $\beta = \frac{\Delta I_C}{\Delta I_B}$

The current gain (or beta, β) is equal to a change in collector current divided by a change in base current.

4. D - MOVING THE SLIDER UPWARD IN THE CIRCUIT OF FIGURE 2-6 CAUSES -- EMITTER CURRENT TO INCREASE.
Moving the slider upward (clockwise) increases base current and collector current, thus increasing their sum, emitter current.

5. C - SUPPOSE THAT, IN THE CIRCUIT OF FIGURE 2-6, D_1 AND C_1 POLARITIES ARE REVERSED WITH ALL OTHER CONNECTIONS REMAINING THE SAME. THE RESULT WILL BE -- Q_1 WILL BE CUT OFF.
Reversing D_1 and C_1 will supply a positive voltage to the base of the PNP transistor driving it into cutoff.

VACUUM TUBE OPERATION

1049

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PRINTED IN USA

The public address amplifier shown above employs 5 vacuum tubes. Three dual triodes and two pentodes are used in a circuit which can provide up to 30 watts of output.

Courtesy Lear Siegler Inc., Bogen Communications Div.

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Great things are made of little things.
—Browning

VACUUM TUBE OPERATION

Although the present day trend is toward transistor and integrated circuit equipment, vacuum tubes still enjoy popularity. There are many applications in which vacuum tubes are more desirable than transistors. These are typically applications including high voltage, high power and high frequencies.

The vacuum tube, like the transistor, is basically an amplifying device. However, internal operation of the two devices is quite different. In a vacuum tube, the flow of free electrons through a vacuum is controlled. In a transistor, the flow of free electrons as well as holes in semiconductor material is controlled.

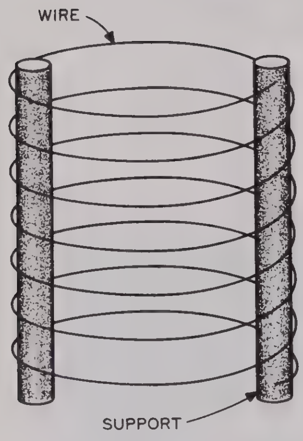


Figure 1

Before examining the triode vacuum tube, let's briefly review the operation of the diode vacuum tube. The diode contains two active elements, the PLATE and CATHODE (or filament). When the cathode is heated, electrons are emitted and form a cloud of electrons around the cathode called the space charge. If the plate is made positive with respect to the cathode, electrons are attracted to the plate and a current flows through the tube. When the plate is made negative with respect to the cathode, the electrons are repelled by the plate and no current flows through the tube. The diode is therefore a switch. When conducting, the diode acts like a closed switch, and when it is reverse biased, it acts like an open switch. There is little control over the amount of electron flow in the diode. Plate current is determined by the external circuit resistance and the supply voltage. By adding a third element to the diode tube, we can control the amount of electron flow through the tube.

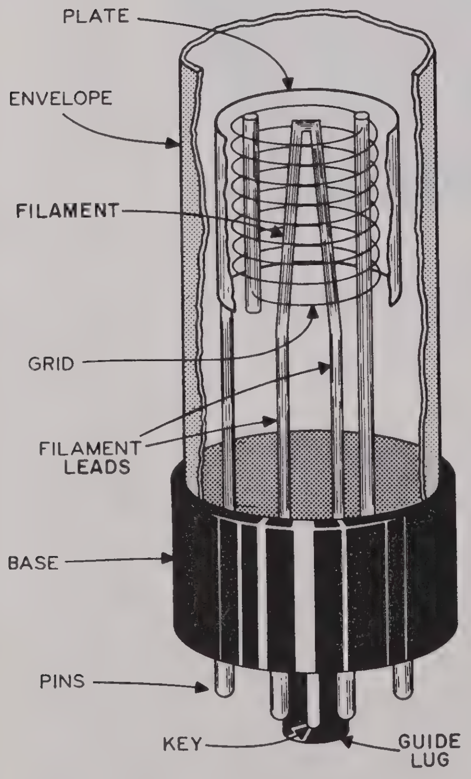


Figure 2

THE TRIODE ELECTRON TUBE

A vacuum tube that contains three active electrodes is called a **TRIODE**. In its most common form, the triode consists of a cathode and a plate between which the third electrode is located. This third active electrode is called the **GRID**. It was given this name because of its grid-like structure. Figure 1 shows one of the several grid structures used. Here, the grid is a single, continuous wire which is wound so it forms a series of oval loops around a pair of vertical support rods.

Figure 2 shows the arrangement of the three electrodes in a typical triode. In this drawing, the plate is cut away to show the grid and filament. As the tube is of the directly-heated type, the filament is the emitter. As shown, the filament is inside the grid, so that the grid is in the path of the electrons moving from the space charge around the filament to the plate. The grid wire is very fine, and the turns are spaced far apart. Therefore, the grid does not physically block an appreciable number of the electrons passing between space charge and plate.

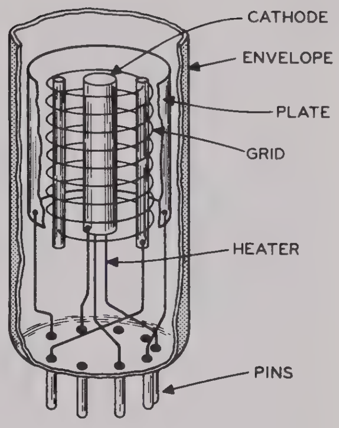


Figure 3

The electrodes in an indirectly-heated triode are shown in the cutaway view of Figure 3. Here, the cathode is shown to be surrounded by the grid which, in turn, is surrounded by the plate. As before, electrons moving from the cathode or space charge must pass between the wires of the grid on their way to the plate. This tube is of the nine-pin miniature type, while that of Figure 2 is of the eight-pin octal type. The nine-pin miniature tube has a glass envelope.

Whatever the physical construction of the vacuum tube triode, the grid has the same purpose. This purpose is to control the flow of electrons from the space charge to the plate. Since the grid is between the cathode and the plate, if we make the grid negative with respect to the cathode, it repels some of the electrons back toward the cathode, so that fewer reach the plate. Hence, the current from the emitter to the plate in a triode depends upon grid potential as well as emitter temperature and plate voltage.

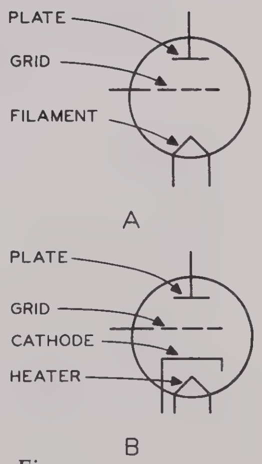


Figure 4

THE TRIODE CIRCUIT

The symbols used for triode vacuum tubes are shown in Figure 4. That of Figure 4A is for tubes with directly-heated emitters, or filament-type tubes. Figure 4B is the symbol for tubes with indirectly-heated emitters, or cathode-heater type tubes. Except for the grid, the symbols are the same as those used for diodes. The grid is drawn between the plate and the filament or cathode to represent its physical location in the tube.

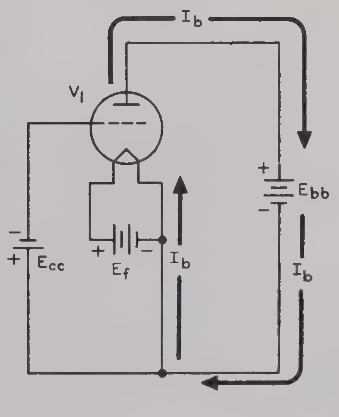


Figure 5

Figure 5 shows the basic circuit of the filament-type triode. Here, battery E_f supplies heater current to the filament of triode V_1. The complete path of this current is from E_f, through the filament, and back to E_f. Battery E_{bb} is called the plate supply. E_{bb} makes the plate voltage positive with respect to the filament. Battery E_{cc} applies a voltage between the grid and filament. E_{cc} is called the grid supply and is connected so that E_{cc} makes the grid of V_1 negative with respect to the filament. The difference of potential between the grid and filament is called **GRID BIAS**. In tube circuits, the potentials of all electrodes are given as (or assumed to be) positive, negative or zero WITH RESPECT TO THE CATHODE POTENTIAL as a reference, unless stated otherwise.

Normally, the grid bias, E_{cc}, is much smaller than the plate supply voltage, E_{bb}. Therefore, with the various voltages applied, electrons leave the space charge around the filament and flow past the grid to the plate. THIS ELECTRON FLOW IS CALLED PLATE CURRENT, AND IS DESIGNATED BY THE SYMBOL I_b. As indicated in Figure 5, the external plate circuit carries the plate current, I_b, in the form of electron flow from the plate of V_1 to the positive terminal of E_{bb} and from the negative terminal of E_{bb} to the filament of V_1. The electrons arriving at the filament replace those emitted into the space charge. This completes the path of the plate current.

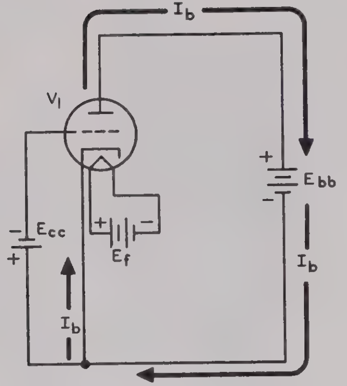


Figure 6

The basic circuit employing an indirectly-heated triode is shown in Figure 6. In this case, battery E_f supplies current to the heater of the tube. Battery E_{bb} applies voltage between the plate and cathode, producing plate current I_b. In this circuit, the grid bias is the difference of potential between the grid and the cathode. Grid bias is provided by E_{cc}. Battery E_{cc} is connected so that it makes the grid negative with respect to the cathode. Plate current in the external plate circuit consists of electron flow from the plate of V_1 to E_{bb}, and from E_{bb} to the cathode of V_1.

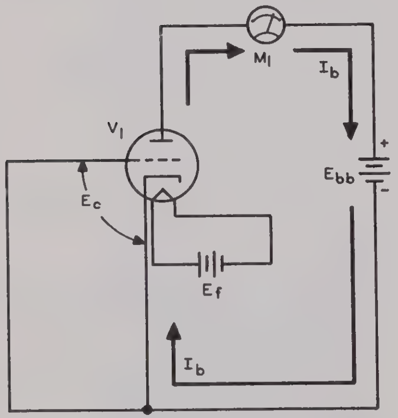


Figure 7

Figures 5 and 6 show the basic dc voltage relationships that exist between the electrodes of vacuum tubes. Various other components are normally added to the circuit to make use of the current flow.

How Tubes Control Current

Because of its location between the cathode and the plate, the grid can control the flow of electrons to the plate. This control of plate current by the grid is the fundamental action of electron tubes other than diodes. This grid is therefore called a **CONTROL GRID**.

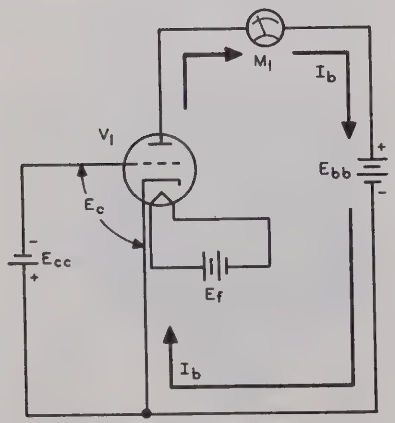


Figure 8

When the grid is made negative with respect to the cathode, it prevents some of the electrons from passing through it to the plate. Remember, electrons have a negative charge, and are therefore repelled by the negative potential on the grid. The more negative the grid is made, the greater the repulsion force of the grid and the smaller the plate current. If the grid is made less negative, the repulsion decreases and the plate current increases.

Figure 7 shows a triode circuit in which the grid is connected directly to the cathode. Because of this connection, there is no difference of potential between these two electrodes. That is, grid-cathode voltage E_c is zero. With the grid at cathode potential, there is no grid-cathode electric field. The grid does not oppose the flow of electrons. Therefore, plate current I_b is large, as indicated by current meter M_1. Applying a negative bias voltage to the grid as shown in Figure 8 reduces the plate current to a lower value, as indicated by the meter. The larger the negative bias, the smaller the plate current.

The relationship between plate current and grid voltage can be shown by means of a graph. Figure 9 shows how the plate current of a typical triode varies with the grid voltage when the plate voltage is equal to 250 volts. This curve is called the grid voltage-plate current characteristic of the tube, or I_bE_c curve.

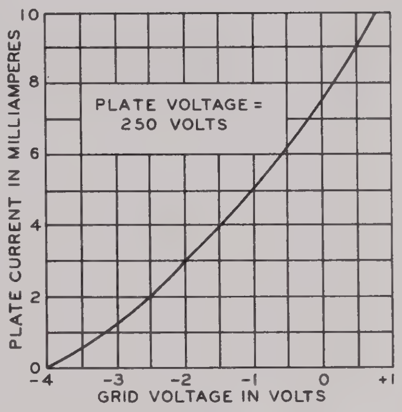


Figure 9

The plate current in milliamperes is given along the left side of the graph, while the scale at the bottom indicates grid voltage or bias in volts. On the grid voltage scale, zero volts is located near the right end, and the values to the left of zero are negative voltages, as indicated. The grid voltage values represent the grid potential with respect to the cathode.

When the grid voltage is zero, as in Figure 7, the curve of Figure 9 shows that the plate current is equal to 7.5 mA. However, the plate current decreases to just above 5 mA when a grid bias of —1 volt is applied. If we increase the negative grid voltage to —2 volts, the plate current decreases to about 3 mA.

As we make the grid more and more negative, plate current continues to decrease. Finally, we reach a negative bias value that reduces the plate current to approximately zero. With the tube represented by Figure 9, this occurs at a grid voltage of —4 volts. This condition is called **PLATE CURRENT CUTOFF**. The grid voltage that causes it is called the **CUT-OFF BIAS**. Grid voltages more negative than the cutoff bias simply cause the plate current to remain at zero. Plate current exists only when the grid voltage is less negative than the cutoff bias.

The plate current values indicated by the curve of Figure 9 for the various grid voltages are true only for a particular plate voltage. When a tube manufacturer publishes a curve of this kind for a given tube, he specifies the plate-to-cathode voltage used when the curve was plotted. In the example of Figure 9, the plate voltage was kept at 250 volts while the grid voltage was set at a series of values over the range indicated. At each grid voltage, the plate currrent was recorded. This set of grid voltage-plate current data was then used to draw the curve.

If the same process is carried out at a higher plate voltage, the plate current is greater than indicated in Figure 9 at each grid voltage value in the range. A curve drawn from these data would be higher on the graph than the

Tube testers like the one shown above provide a convenient means of checking the operation of vacuum tubes. This particular unit also includes provisions for testing television cathode-ray tubes.
Courtesy Seco Electronics Corp.

one shown. Likewise, for a lower plate voltage, the curve would be lower than the one shown because the plate current would be less than indicated for each grid voltage.

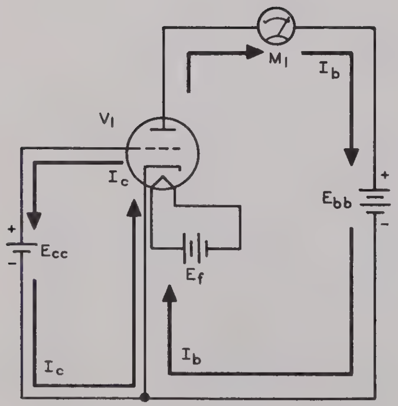


Figure 10

In the normal operation of most triode tubes, a grid bias is applied that lies somewhere between zero and the cutoff bias. The applied input signal then causes the grid voltage to become either more or less negative than the bias for an interval of time, or to vary continuously around the bias value. This results in corresponding changes in plate current. Very seldom does the input signal in an amplifier circuit cause the grid to become positive with respect to the cathode. In most applications, a positive grid voltage is considered abnormal operation of the tube. A positive bias can be provided, as shown in Figure 10, where E_{cc} is connected with its positive terminal to the grid and its negative terminal to the cathode. The curve of Figure 9 shows that plate current increases when the grid becomes positive. When the grid voltage is +.75 volt, the plate current becomes 10 mA.

When the grid is positive, both the grid and the plate pull electrons from the space charge. Most of the electrons moving toward the grid pass between the grid wires, attracted to the highly positive plate. This causes the increase in plate current. With a positive grid, enough plate current can be drawn to damage the tube as well as external circuit components. However, some of the electrons are captured by the grid. These flow through the external grid circuit consisting of E_{cc} in Figure 10, back to the cathode. This flow is called grid current (I_c). Since the grid is taking electrons that should go to the plate, grid current causes undesirable operation in most tube circuits. Therefore, except in certain applications, the tube is normally operated so that the grid voltage is never permitted to become positive.

The basic operation of the triode vacuum tube makes use of variations of the negative grid voltage to cause desirable changes in the plate current. Because it is much closer to the cathode, the grid has much greater control over plate current than does the plate.

How Tubes Amplify Voltage

We have mentioned that vacuum tubes are used mainly for amplification and control. The term "amplify" means to make larger or increase the amplitude of. The process of amplifying is called **AMPLIFICATION**. A device that amplifies is called an amplifier. Usually, an amplifier consists of a circuit containing a number of components, including one or more tubes or other control devices.

Figure 11 shows a triode voltage amplifier circuit. Here, the grid circuit contains an alternating voltage source, E_{IN}, in series with the grid bias supply, E_{cc}. Since E_{IN} reverses its polarity as each alternation begins, it aids E_{cc} during one alternation and opposes it during the next. The total voltage between the grid and cathode is equal to E_{IN} and E_{cc} combined.

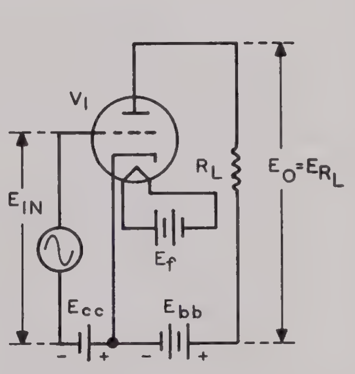


Figure 11

When the upper terminal of E_{IN} is negative, the total grid voltage is the sum of E_{cc} and E_{IN}. During the other alternation, when the upper terminal of E_{IN} is positive, the grid voltage is equal to the difference between E_{cc} and E_{IN}. Since E_{IN} varies through the alternation, this sum also varies. The peak value of E_{IN} in this figure is less than E_{cc}, so the positive peaks of E_{IN} cannot make the grid positive with respect to the cathode. Therefore, the grid voltage varies, but always remains more negative than the cathode.

In the plate circuit of Figure 11, resistor R_L is connected in series between the plate of triode V_1 and the positive terminal of E_{bb}. Resistor R_L is called the PLATE LOAD RESISTOR. V_1 plate current flowing through R_L develops the amplifier's output signal. As the grid voltage becomes more negative, the triode plate current decreases. In turn, the voltage drop across

R_L decreases. Plate supply voltage E_{bb} is applied to the two resistive components, V_1 and R_L, in series. Therefore, as the drop across R_L decreases, the plate voltage of V_1 increases, and as the drop across R_L increases, V_1 plate voltage decreases.

As mentioned previously, triode V_1 and load resistor R_L form a voltage divider, dividing E_{bb} between them. As input voltage E_{IN} varies during each cycle, it causes the grid voltage to vary, changing the V_1 plate current. When the V_1 plate current increases, the drop across R_L (E_O) increases, and the V_1 plate voltage decreases. When E_{IN} causes the V_1 plate current to decrease (by making the grid more negative), the voltage drop across R_L decreases, thus increasing the V_1 plate voltage. Remember, the sum of the voltage drop across R_L and the V_1 plate voltage equals the plate supply voltage. In the form of equation:

$$E_{bb} = E_{R_L} + E_b \tag{1}$$

Thus, the varying voltage E_{IN} makes the V_1 plate current increase and decrease during each cycle. These V_1 plate current changes result in variations in the voltage across load resistor R_L. The voltage variations across R_L are represented in the figure as E_O. Voltage E_{IN} is the input to the circuit, and E_O is the output. Normally, the circuit values are selected so that E_O has greater amplitude than E_{IN}. The circuit is then said to amplify, because E_O is an amplified or enlarged version of E_{IN}. The circuit of Figure 11 is called a voltage amplifier.

As an example of the operation of a circuit like that of Figure 11, suppose E_{cc} equals —2 volts, E_{bb} equals 260 volts, and R_L equals 100,000 ohms. At the instant when voltage E_{IN} is equal to zero, the grid voltage is equal to E_{cc}, or —2 volts. Suppose this grid voltage causes triode V_1 to have a plate current of 2 mA. The voltage drop across R_L is therefore $E_{R_L} = 1 \times 10^5$ ohms $\times 2 \times 10^{-3}$ amperes, or 200 volts. Since $E_{bb} = E_{R_L} + E_b$, the plate voltage E_b is equal to $E_{bb} - E_{R_L} = 260$ volts — 200 volts, or 60 volts.

If E_{IN} becomes 1 volt negative, it aids E_{cc}, making the grid voltage change to $(-2) + (-1)$, or —3 volts. Suppose this decreases the V_1 plate current to 1.8 mA. The voltage drop across R_L is therefore $E_{R_L} = 1 \times 10^5$ ohms $\times 1.8 \times 10^{-3}$ amperes, or 180 volts. The plate voltage is $E_b = 260$ volts — 180 volts, or 80 volts.

If E_{IN} becomes 1 volt positive, it opposes E_{cc}, making the grid voltage change to $-2 + 1$, or —1 volt. Suppose this increases V_1 plate current to 2.17

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE TRIODE ELECTRON TUBE

THE TRIODE CIRCUIT

HOW TUBES CONTROL CURRENT

1. What is a triode tube?

2. In typical commercial electron tubes like those illustrated in Figures 2 and 3, (a) the grid is between the cathode and plate, (b) the plate is between the grid and cathode, (c) the cathode is between the plate and grid.

3. What element of an electron tube emits electrons?

4. In a triode tube, the flow of electrons from the space charge to the plate (a) is always prevented by the grid, (b) can be controlled by the grid, (c) is independent of the grid.

5. In a triode vacuum tube circuit, the grid is normally (a) negative with respect to the plate, (b) positive with respect to the filament, (c) positive with respect to the plate.

6. What are the polarities of the voltages on the grid and on the plate in respect to the cathode voltage of a vacuum tube under normal operating conditions?

7. What do the supplies labeled E_{bb} and E_{cc} represent in a vacuum tube circuit?

8. What happens to the plate current in a triode tube as the grid is made more negative with respect to the cathode?

9. Explain how the grid controls plate current in a triode tube.

10. What is plate current cutoff?

11. If you were going to use the tube represented by Figure 9 as an amplifier, what value of grid bias would you employ to produce a plate current of 2 mA?

12. The plate current values indicated by a single curve like that of Figure 9 are true for (a) any plate voltage, (b) zero plate voltage only, (c) a given plate voltage only.

13. In most applications, the grid voltage of a triode usually is kept (a) negative, (b) zero, (c) positive.

14. When the grid is made positive with respect to the cathode, is there electron flow in the grid circuit?

mA. The voltage drop across R_L is therefore $E_{R_L} = 1 \times 10^5$ ohms $\times$ 2.17 $\times 10^{-3}$ amperes, or 217 volts. The V_1 plate voltage then equals $E_b = 260$ volts $-$ 217 volts, or 43 volts.

In this example, input voltage E_{IN} varies from -1 to $+1$ volt, a total variation of 2 volts. The voltage across R_L varies from 180 volts to 217 volts, a total of 37 volts. Thus, the amplified output voltage, E_O, has a peak-to-peak value of 37 volts. This is a little over 18 times the peak-to-peak value of E_{IN}.

OTHER TYPES OF TUBES

Figures 2 and 3 earlier in the lesson show two common methods of construction for triode tubes. Modern tube technology has developed a wide variety of tube types suited for particular applications.

Ceramic Triodes

Figure 12 shows the arrangement of electrodes in a ceramic triode. Here, the cathode is a flat disc supported above the heater by a metal cylinder. This cylinder provides a conductive connection between the cathode and the metal cathode ring. The ring is the means of connecting the cathode to an external circuit. The grid is a circular grill mounted directly above the cathode. It is connected by the grid ring to an external circuit. The plate, or anode, is a large disc at the top of the tube, and a projection at its center extends downward toward the grid. Finally, the heater connects to the external circuit by means of a pair of metal buttons. The remainder of the tube consists of three circular ceramic insulators which hold the electrodes in position and prevent them from touching each other.

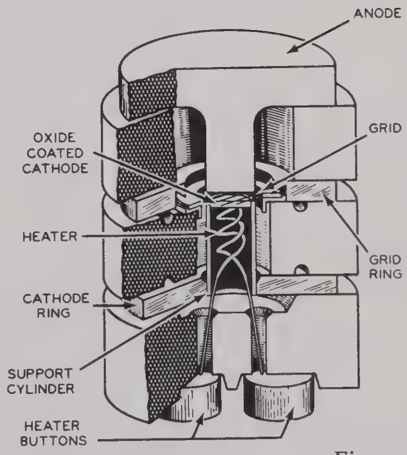


Figure 12

Nuvistors

Figure 13 shows a triode version of a tube made almost entirely of metal. A strong ceramic base wafer serves as a platform which supports the electrodes. Each electrode is solidly supported by a cone-shaped metal flange. The tube employs an indirectly-heated cathode. The heater leads extend down through the open, lower end of the cathode and the base wafer. The smallest of the three support flanges holds the cathode over the heater. The next larger flange fits over the cathode flange without touching it, and supports the grid. The largest flange fits over the grid flange and supports the

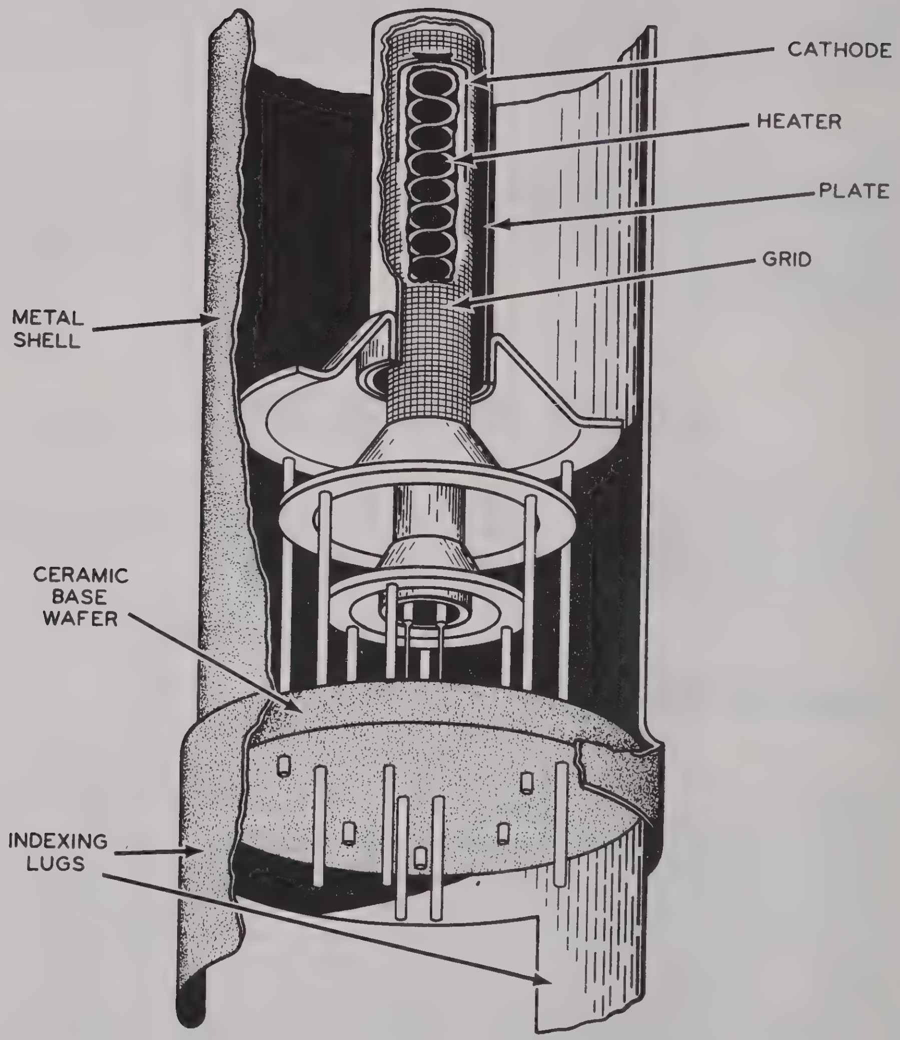
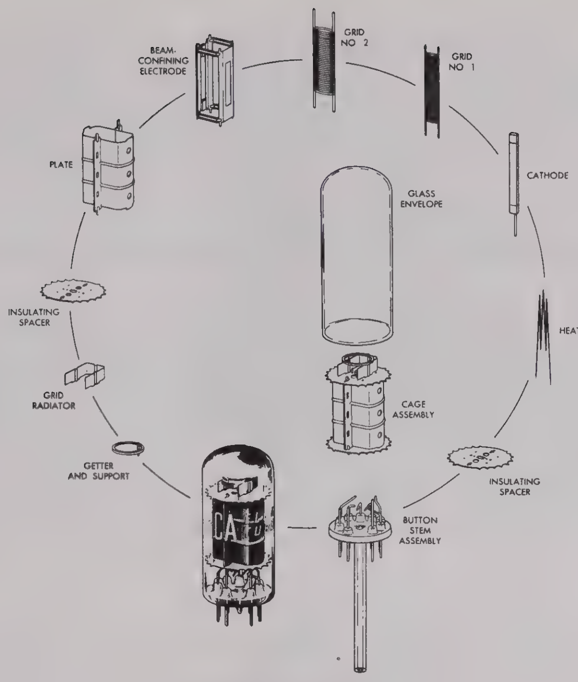


Figure 13

plate. All three flanges are supported by leads which are held in place by the base wafer.

Some of the leads pass down through the wafer to connect the electrodes to external circuits. The electrodes are positioned with the grid between the cathode and plate, as in the tube of Figure 3. The metal tube envelope of Figure 13 has two extensions downward from the base called the indexing lugs. These lugs protect the leads during insertion into the tube socket and permit rapid insertion. A tube having this construction is called a **NUVISTOR**. Tubes of this type are extremely rugged, though very small in size.



Parts of a Novar Tube

The above photo shows the construction of a Novar-type (9-pin) tube.

Courtesy RCA Corporation

Tetrodes

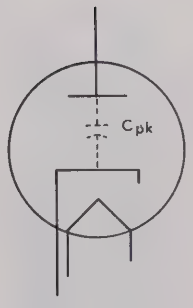


Figure 14

Whenever two conductive objects are separated by an insulating material, they form a capacitor. The electrodes in a vacuum tube are an example. Figure 14 shows the capacitance between the plate and cathode of a diode. This capacitance is called **INTERELECTRODE CAPACITANCE** since it appears between the electrodes of the tube. This capacitance is designated C_{pk} to indicate that it is the capacitance between the plate and cathode electrodes. Usually, the value of C_{pk} is quite small, ranging from about 1 to 10 picofarads.

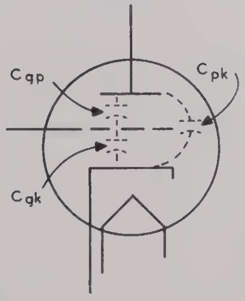


Figure 15

In the triode, the grid shields the plate from the cathode to some extent, thus reducing the plate-cathode capacitance. Since the grid is a conductive material and is insulated from both the cathode and the plate, the triode has interelectrode capacitance between the grid and plate (C_{gp}), between the grid and cathode (C_{gk}), and between the plate and cathode (C_{pk}). These capacitances are indicated in Figure 15.

The capacitance between the grid and the plate often has an undesirable effect on the operation of a triode. An input signal voltage applied to the grid causes the voltage on the plate of the tube to change due to plate current changes. The plate voltage changes cause the grid-plate interelectrode capacitance to charge and discharge. In this way, the capacitance couples the signal from the plate circuit back to the grid circuit. If a great deal of the signal is coupled back to the grid, it interferes with normal tube operation. The tube begins to amplify its own output signal instead of the input signal. This action occurs more readily at high frequencies than at low frequencies.

To reduce the grid-to-plate capacitance, a type of tube called a **TETRODE** has another grid which is located between the control grid and the plate. This second grid is called the **SCREEN GRID**. Its purpose is to shield the control grid from the capacitive effect that the plate has on the control grid. The name tetrode indicates that the tube has four electrodes. The emitter (cathode or filament) is counted as one electrode, whether it is heated directly or indirectly.

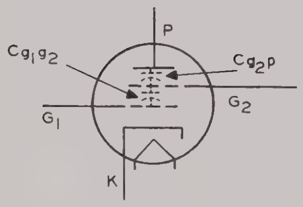


Figure 16

Figure 16 gives the schematic symbol of a tetrode tube. Here, grid G_1, nearest the cathode, serves the function of the grid in the triode. For this reason, it is called the control grid. Grid G_2, nearest the plate, is the screen grid. The dashed-line capacitors indicate that the screen grid breaks up the capacitance between control grid and plate into two capacitances in series. These consist of the capacitance between screen grid and plate (C_{g_2p}) and the capacitance between control grid and screen grid ($C_{g_1g_2}$).

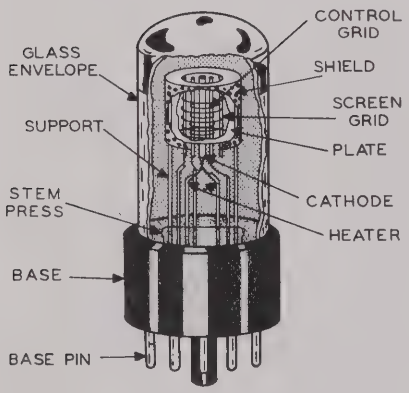


Figure 17

Figure 17 shows a cutaway view of a tetrode. Its structure is much like that of a triode. The electrodes are mounted on wire supports embedded in a glass holder called the stem press. The wires for external circuit connections extend down through the base pins. The cathode surrounds the heater and the control grid surrounds the cathode. The screen grid is constructed in the same manner as the control grid and is mounted around the outside of the control grid. The plate surrounds the screen grid. Finally, in the tube shown here, a perforated metal shield is placed around the outside of the plate and connected electrically to the screen grid. Its purpose is to shield the electrodes from external magnetic and electric fields.

Normally, the screen grid is operated at a positive potential, as shown in the basic tetrode circuit of Figure 18. The voltage divider consisting of R_1 and R_2 causes the screen voltage to be a little less positive than the plate voltage. The electric field of the plate ends at the screen grid. Therefore, the plate itself exerts very little pull on the electrons in the space charge near the cathode. However, the positive screen grid attracts the electrons, much like the plate attracts electrons in a triode.

As the electrons arrive at the screen grid, a few are captured by the screen grid. This produces a screen grid current consisting of a flow of electrons from the screen grid to the junction of R_1 and R_2, through R_1 to E_{bb} and from E_{bb} to the cathode. But most of the electrons pass through the screen grid, because of its open structure, and move into the plate's field, which then pulls them to the plate.

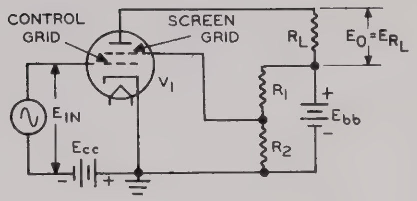


Figure 18

In a tetrode tube, the screen grid has a much greater effect on the plate current than does the plate. This is because the electric field of the plate does not extend into the region between the screen grid and cathode. With a given negative bias on the control grid, the screen grid potential determines the number of electrons attracted from the space charge. Large changes of plate voltage can occur without affecting this flow of electrons from space charge to screen grid. As mentioned, most of the electrons continue on to the plate, since the screen grid takes only a few electrons out of the stream. The screen current serves no useful purpose and, therefore, it is desirable that screen current be as small as possible.

Pentodes

When electrons strike a metal surface at high speed, they knock other electrons from the surface. The electrons knocked out in this manner are called secondary electrons. Since the action consists of electrons leaving a solid material, it is a form of electron emission. Because the emitted electrons are referred to as secondary electrons, the action is known as **SECONDARY EMISSION**.

Secondary emission takes place in vacuum tubes as electrons strike the various electrodes. The most important of these emissions is that which occurs at the plate, since nearly all the electrons coming from the space charge strike this electrode. In diodes and triodes, all the secondary electrons are attracted back to the plate, so there is no loss of plate current. However, in the tetrode, large numbers of the secondary electrons emitted from the plate are attracted to the positive screen grid. This action increases the screen current while decreasing the plate current. Figure 19 shows the flow of secondary electrons from the plate to the screen grid. This flow is greatest when the screen grid is more positive than the plate.

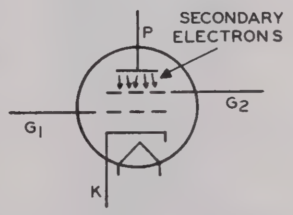


Figure 19

As mentioned, the screen current is of no use insofar as the tube operation is concerned. The collection of secondary electrons by the screen grid can be prevented by providing a region of very low or zero potential at some point between the screen grid and the plate. This region is then highly negative with respect to the plate. The strong electric field between this region and the plate causes the secondary electrons to move back to the plate, thus preventing them from going to the screen grid.

The photo above shows a typical beam power pentode in a 7-pin miniature envelope.
Courtesy RCA Corporation

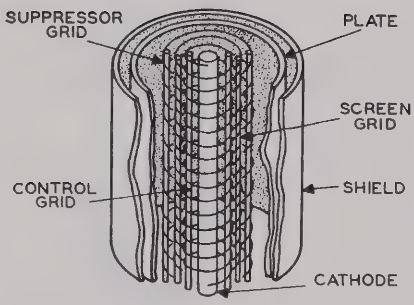


Figure 20

One method of producing a zero potential region between the plate and screen is the use of a third grid situated at this point. This third grid is called the **SUPPRESSOR GRID**. Physically, it surrounds the screen grid and is in turn surrounded by the plate. Its zero potential is provided by electrically connecting it to the cathode. Since this tube has five active electrodes, it is called a **PENTODE**.

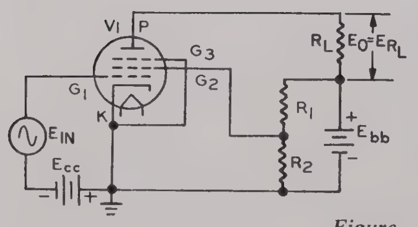


Figure 21

A cutaway drawing of the electrodes in a pentode is shown in Figure 20. The cathode in the center is surrounded in turn by the control grid, the screen grid, the suppressor grid, the plate and, finally, a shield. The shield (often connected to the cathode) is used to protect the tube operation from stray signals. Not all pentodes have shields. The three grids are sometimes designated G_1, G_2 and G_3, in the order of their positions outward from the cathode. These designations are used in Figure 21, which shows a pentode tube symbol, V_1, and the basic pentode circuit. In this example, the suppressor grid and cathode are connected externally. In some pentodes, this connection is made internally within the tube. Not shown is the filament which is inside the cathode.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

THE TRIODE CIRCUIT

HOW TUBES AMPLIFY VOLTAGE

OTHER TYPES OF TUBES

CERAMIC TRIODES

NUVISTORS

TETRODES

15. In the circuit of Figure 11, how does the input signal vary the grid voltage on V_1?

16. In an amplifier circuit like that of Figure 11, the peak value of E_{IN} must be less than grid bias E_{cc} to prevent the grid from becoming positive with respect to the cathode. True or False?

17. When the grid of a triode tube becomes more negative, plate current (a) decreases, (b) is not affected, (c) increases.

18. What is the purpose of R_L in the circuit of Figure 11?

19. When the input voltage causes the plate current to increase, the voltage across the load resistor (a) remains constant, (b) decreases, (c) increases.

20. Suppose the grid voltage is such that at the tube plate current is 3 mA in an amplifier circuit like that of Figure 11. If $E_{bb} = 300$ volts and $R_L = 90{,}000$ ohms, what are the voltages across R_L and E_b?

21. What do the following terms represent: C_{pk}, C_{gk} and C_{gp}?

22. Generally, which interelectrode capacitance most adversely affects the operation of a triode?

23. The purpose of the screen grid in the tetrode is to reduce the (a) grid-to-plate interelectrode capacitance, (b) plate current, (c) emission from the cathode.

24. Normally, the potential of the screen grid is (a) equal to that of the cathode, (b) positive with respect to the cathode, (c) negative with respect to the cathode.

25. Under normal conditions, does current flow in the screen grid circuit?

26. In a tetrode, which has the greatest control of plate current—the plate or the screen grid?

Except for the connection from the cathode to the suppressor grid, the pentode circuit is like that of the tetrode in Figure 18. That is, E_{cc} provides negative bias voltage for the control grid, E_{IN} applies a signal voltage to the control grid, and E_{bb} supplies positive voltage to the plate. The positive voltage for the screen grid is obtained at the junction of R_1 and R_2. R_L is the plate load resistor, across which the circuit output is produced. The control grid exerts the greatest control over the plate current of a triode, tetrode or pentode.

The circuits of Figures 18 and 21 amplify in the same way as does the triode circuit of Figure 11.

Beam Power Tubes

The **BEAM POWER TUBE** is a special tetrode that has been designed to eliminate the flow of secondary electrons from the plate to the screen grid. Historically, it was developed later than the pentode. In the beam power tube, electrons flowing between the screen grid and plate form a space charge. With respect to the plate, the space charge is very negative, since it is made up of electrons. Therefore, secondary electrons coming from the plate are repelled back to the plate by the space charge. Thus, this space charge acts much like the suppressor grid in the pentode.

Special construction is necessary, however, to form a space charge with enough density to perform this function properly. A cutaway view of the beam power tube is given in Figure 22. The distance between the screen grid and the plate is made rather long. This allows time for the space charge to form, permitting maximum plate current.

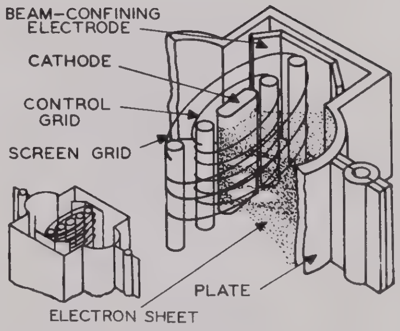


Figure 22

The density of the space charge is further increased by confining the electrons to relatively narrow beams. A beam-confining electrode is located at each rounded side of the cathode. These electrodes, or plates, are electrically connected to the cathode so that they repel electrons and force them to flow only between the beam-confining electrodes. The cathode is flattened so that most of the emission occurs in the direction of the beams. Each screen grid turn is between a turn of the control grid and the plate. Thus, because of the control grid wires, the screen grid cannot be seen from the cathode. From the standpoint of the cathode, the screen grid is in the electrical shadow of the control grid. Therefore, the electrons that flow through the spaces between the wires of the control grid also flow through the spaces between the screen grid wires. This forms the electron beams into a series of sheets, one above the other. The result is that a very strong concentration of electrons produces the space charge between the plate and screen grid.

The space charge electrons move continually to the plate. As with other tube types, the number of electrons that enter the plate at any instant depends on the voltage of the control grid. Very few of the electrons moving toward the plate are able to strike the screen grid directly. Therefore, the screen current of a beam power tube is much lower than that of a pentode tube with a suppressor grid.

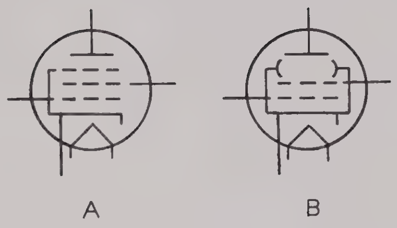


Figure 23

The schematic symbol for the beam power tube commonly takes either of two forms. One is shown in Figure 23A. This is the same symbol that is used for a pentode tube in which the suppressor grid is internally connected to the cathode. So far as the beam power tube is concerned, the suppressor grid in the symbol merely represents the action of the space charge explained above. The other form of the beam power tube symbol is shown in Figure 23B. Here, the beam-confining electrodes are represented by small, curved lines shown connected to the cathode. The basic circuit of the beam power tube is like that of Figure 21.

An advantage of the low screen current is that little power is wasted by dissipation in the screen. Also, the tube can be operated at high plate currents without causing the screen grid to become so warm that it emits electrons. A further advantage is that relatively low wattage resistors can be used in the divider that supplies the screen voltage.

Multigrid Tubes

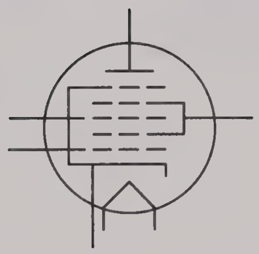


Figure 24

A number of tubes with more than three grids have been developed for special application. Of great importance among these is the **PENTAGRID TUBE,** a unit having five grids. Figure 24 shows the symbol of one pentagrid type. Including the plate and cathode, there is a total of seven active electrodes. The first and third grids are independent control electrodes to which signals or other control voltages may be applied. The second and fourth grids are internally connected screen grids. The second grid shields the first and third grids from each other. Finally, the fifth grid is the suppressor grid which, as shown, connects internally to the cathode.

One common application of the pentagrid tube is that of a gated amplifier. The first and third grids each affect the electron flow from the region of the cathode to the plate. Therefore, the final plate current varies according to the signal or control voltages on both of these grids. A second common application is that of a pentagrid converter in receivers. In this case, the tube serves the functions of both oscillator and mixer.

Combination Tubes

To save space, the elements of two or more complete tubes are often placed in a single envelope. Some of these combinations use a common cathode. In others, there are separate cathodes. One such combination is the double triode, the symbol of which is shown in Figure 25. The two triodes are electrically independent of each other so they can operate without interfering with each other. The heater in duotriode tubes is often center tapped, as shown in Figure 25. This allows a series or parallel operation of the heater elements for 12-volt or 6-volt operation. Another example is the duodiode-triode of Figure 26. This unit consists of three tubes (two diodes and a triode) which use the same cathode. Figure 27 shows a triode-pentode with a common cathode again serving for both sections.

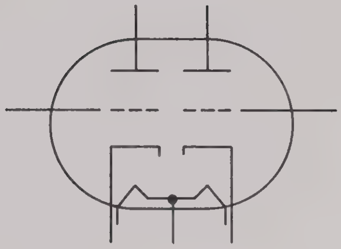


Figure 25

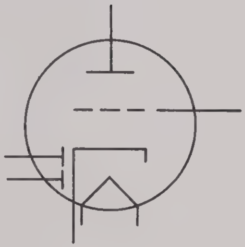


Figure 26

More than one tube in one envelope is the basis of a relatively new line of tubes called **COMPACTRONS.** The main difference between these and the other multiple-tube units is that the compactrons are quite small in size, despite the fact that the envelope contains the elements of two or more tubes. Figure 28 shows the symbol of one compactron type. As shown, this unit consists of a pentagrid tube and a pentode tube. A second compactron is shown in Figure 29. In this case, within one envelope are a diode-triode, a pentode and a diode. Since the diode-triode is a double tube to begin with, this compactron really contains four tubes. In both compactrons shown, the heaters are connected in series internally, as in the double triode of Figure 25.

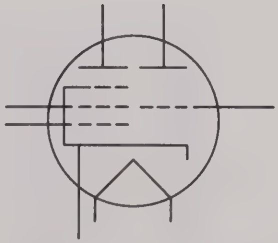


Figure 27

TUBE CLASSIFICATION

Electron tubes are classified in several ways. One method is based on the number of active electrodes in the tube. Thus, we have the diodes, triodes, tetrodes and pentodes already described. Also, tubes with six elements or electrodes are called hexodes, those with seven electrodes are heptodes, and those with eight electrodes are called octodes. A second method of classifying tubes is according to their use: as rectifier, amplifier, oscillator, picture tube, camera tube, X-ray tube, etc.

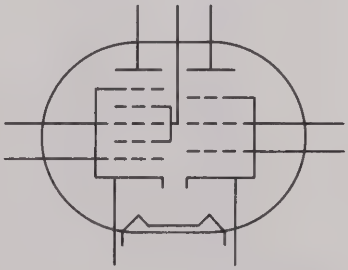


Figure 28

Diodes, triodes, tetrodes, pentodes and beam power tubes all can be found in a variety of envelopes and bases. Hence, they are also designated as metal, ceramic, glass, glass octal, miniature, sub-miniature, lock-in, glass lock-in, novar, nuvistor and glass noval.

A **HARD TUBE** is one which has been highly evacuated of air and then sealed. Because nearly all of its air has been removed, a hard tube is called a vacuum tube. A **SOFT TUBE** is one that has been evacuated, and then a small amount of some gas placed in it. It is also called a gas-filled tube.

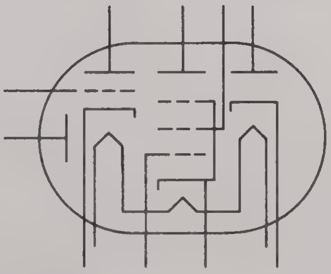
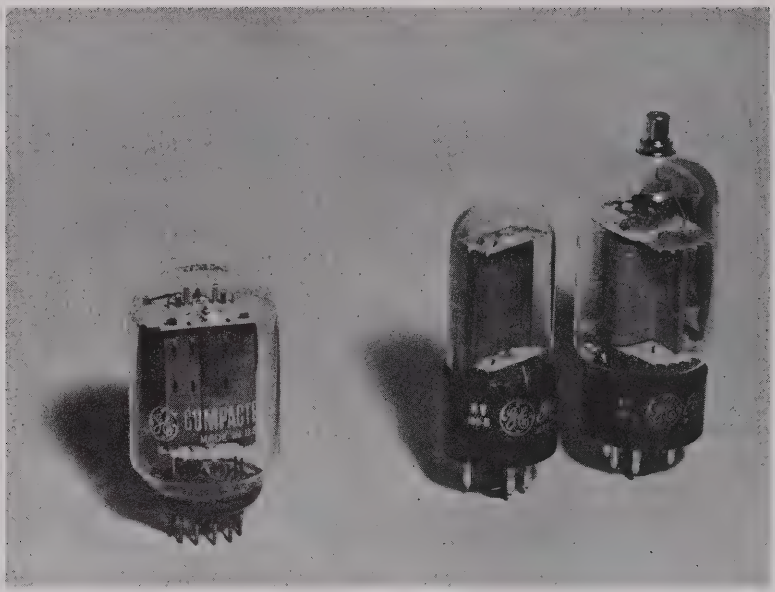


Figure 29



The compactron tube shown at the left in this photo takes the place of the diode and pentode shown at the right.

Courtesy General Electric Co.

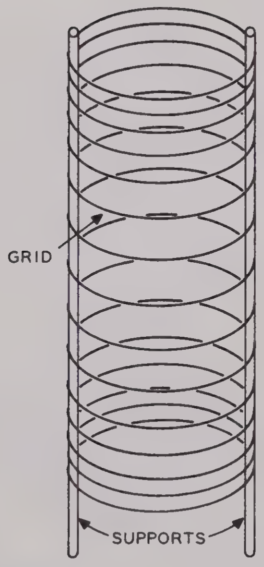


Figure 30

Another tube classification describes the tube's ability to amplify. The Greek letter mu (μ) represents the amplification, or how many times greater the output voltage is compared to the input voltage applied to the control grid. When the control grid wires are wound close together, the amplification is high. A tube with this type of grid is called a high-mu tube. In a low-mu tube, the grid wires are spaced farther apart.

It is sometimes desirable that the amplification be variable. For this purpose, a variable-mu tube is employed. It has a grid wound as shown in Figure 30. Here, the grid has open spacing at the center and close spacing at the ends. When a weak signal is applied to the grid, the close spacing near the ends of the grid has the most control on the plate current, and the amplification is high. With strong signals, electron flow is cut off near the ends of the grid, and only the open spacing at the center controls the plate current. Amplification is then reduced.

MAXIMUM RATINGS

Certain maximum ratings must be observed to insure that a tube operates properly. Exceeding these ratings may damage or shorten the life of the tube. One important rating is the maximum plate dissipation. Its value in

The following Practice Exercise questions cover the subjects which you have just studied. They are:

- **OTHER TYPES OF TUBES**
  - **PENTODES**
  - **BEAM POWER TUBES**
  - **MULTIGRID TUBES**
  - **COMBINATION TUBES**
- **TUBE CLASSIFICATION**
- **MAXIMUM RATINGS**

27. What is the function of the suppressor grid?

28. Draw the schematic symbols for a triode, tetrode and pentode. Show indirectly heated tubes. Label the elements with K, P, G or G_1, G_2 and G_3.

29. **How is secondary emission eliminated in the beam power tube?**

30. **Is the screen current higher in a beam power tube than in a comparable pentode?**

31. **How many active elements are there in a pentagrid tube?**

32. **What is the difference between a hard tube and a soft tube?**

33. **In a vacuum tube, the spacing of the control grid wires affects the mu of the tube. True or False?**

34. **How is the grid constructed in a variable-mu tube?**

35. **What happens if the peak heater-cathode voltage rating is exceeded?**

36. **What is meant by the maximum plate dissipation rating of a vacuum tube?**

watts indicates the maximum electric energy that can be converted into heat and dissipated safely and continuously by the plate. This heat is generated by the electrons as they bombard the plate at high velocity.

Another maximum rating is the peak heater-cathode voltage. It is important when high voltages are applied between the heater and the cathode. This rating specifies the highest voltage that can safely be applied between the heater and cathode without breaking down the insulation.

SUMMARY

An electron tube is a group of two or more electrodes, called elements, enclosed in an envelope, with leads or conducting surfaces extending through the envelope or base for connecting the elements to external circuits. The elements or electrodes are of metal, and are therefore conductive. They are electrically separated and physically supported by insulating materials. The envelope is made of glass, metal or ceramic. An electron tube from which the air has been removed is called a vacuum tube. A tube is named according to the number of active electrodes it contains. Thus, one with three such electrodes is a triode, one with four is a tetrode, and so on.

Normally, the grid nearest the cathode in a tube is called the control grid. It is called this because it has the greatest control over the flow of electrons moving from the space charge near the cathode to the plate. The plate current in a vacuum tube is normally controlled by varying the potential of the control grid. Voltage amplification is obtained by applying a signal voltage to the control grid of a tube. This results in a larger variation of voltage in the plate circuit. The plate circuit voltage change follows the form of the signal applied to the control grid. Therefore, the voltage variation, or signal, in the plate circuit is an enlarged or amplified signal applied to the control grid.

Progress in tube design in recent years has been in two general directions. One is toward increased circuit capabilities. These include operation at extremely high frequencies, higher power efficiency, greater control by the grid over plate current and smaller size. The other direction is in the areas of greater tolerance to environment and greater reliability. These are obtained by the use of new materials and construction methods. They include synthetic micas for insulation, multiple-layer composite plate metals, new heater and cathode materials, and ceramic envelopes.

IMPORTANT DEFINITIONS

AMPLIFICATION — The process of making larger or increasing amplitude.

BEAM POWER TUBE — A tetrode power tube designed to eliminate the flow of secondary electrons from the plate to the screen grid.

COMPACTRONS — Units consisting of two or more tubes in one envelope. The envelope is smaller in size than in the older multi-tube units.

CONTROL GRID — The element in an electron tube that has the most control over the plate current.

CUTOFF BIAS — The negative grid voltage required to reduce plate current to zero in an electron tube.

GRID — An electrode located between the cathode and the plate.

GRID BIAS — DC difference in potential between the grid and the cathode or the filament.

HARD TUBE — A highly evacuated electron tube. A vacuum tube.

INTERELECTRODE CAPACITANCE — The capacitance existing between the electrodes of an electron tube.

NUVISTOR — A very small cylindrical tube in which the electrodes consist of concentric cylinders supported in an open-ended cantilever fashion by a series of tripod-like structures.

PENTAGRID TUBE — A tube having five grids (usually with a total of seven elements).

PENTODE — A tube having five electrodes other than the heater.

PLATE CURRENT CUTOFF — The condition that occurs when the negative grid voltage is high enough to reduce plate current to zero.

SCREEN GRID — A grid located between the control grid and the plate and having a positive potential applied to it.

SECONDARY EMISSION — Emission of electrons from the plate of a tube due to electrons striking the plate at high speed.

SOFT TUBE — An electron tube containing gas at low pressure. A gas tube.

SUPPRESSOR GRID — A grid, located between the screen grid and the plate, which is normally operated at cathode potential.

TETRODE — A tube with four active electrodes other than the heater.

TRIODE — A tube having three active electrodes other than the heater.

ESSENTIAL SYMBOLS AND EQUATIONS

E_{bb}	Plate supply voltage
E_{cc}	Grid supply voltage
E_f	Filament supply voltage
E_c	Grid-to-cathode voltage
E_b	Plate-to-cathode voltage
I_b	Plate current
E_{R_L}	Voltage drop across load resistor
C_{pk}	Plate-to-cathode capacitance
C_{gk}	Grid-to-cathode capacitance
C_{gp}	Grid-to-plate capacitance

$$E_{bb} = E_{R_L} + E_b \tag{1}$$

PRACTICE EXERCISE SOLUTIONS

1. **A triode is a tube having 3 active electrodes.**

2. **(a) the grid is between the cathode and plate.**

3. **The cathode (indirectly heated by the heater) or the filament (directly heated) emits electrons.**

4. **(b) can be controlled by the grid.**

5. **(a) negative with respect to the plate. — Since the grid is negative with respect to the filament and the plate is positive with respect to the filament, the grid must be negative with respect to the plate.**

6. **Under normal conditions the plate of a vacuum tube is made positive with respect to the cathode while the grid is made negative with respect to the cathode.**

7. **In a vacuum tube circuit, E_{bb} represents the plate supply voltage and E_{cc} represents the grid supply voltage.**

8. **Increasing the negative grid voltage on a triode tube decreases plate current.**

9. **The negative potential on the grid opposes the negatively charged electrons. The resultant electric field set up between grid and cathode opposes the movement of electrons from cathode to plate. Increasing the negative grid voltage increases this field, reducing the flow of electrons from cathode to plate.**

10. **Plate current cutoff is the condition that occurs when the negative grid voltage is high enough to reduce the plate current to zero. The grid voltage at which plate current cutoff occurs is called the cutoff bias.**

11. **—2.5 volts (approximately). — Locate 2 mA on the scale at the left. Follow the horizontal line to the right to the curve. From this point, follow the vertical line down to where it meets the grid voltage scale slightly to the left of —2.5 volts.**

12. **(c) a given plate voltage only.**

13. **(a) negative.**

PRACTICE EXERCISE SOLUTIONS (Continued)

14. Yes — When the grid is positive with respect to the cathode, it attracts electrons and grid current begins. This action is undesirable in most circuits and can cause improper circuit operation and possibly damage the tube.

15. In the circuit of Figure 11, the input signal, E_{IN}, is in series with the grid supply, E_{cc}. The sum of these two voltages determines the grid-cathode voltage, E_c. When the upper end of E_{IN} is positive, it opposes the voltage provided by E_{cc}, and the grid voltage, E_c, becomes less negative. On the other alternation when the upper end of E_{IN} is negative, it aids the voltage provided by E_{cc} and the grid voltage, E_c, becomes more negative.

16. True — If the peak value of E_{IN} is greater than E_{cc}, the net grid voltage, E_c, becomes positive during the positive peaks of E_{IN}.

17. (a) decreases. — Increasing the negative grid voltage increases the tube's resistance, decreasing plate current.

18. The purpose of R_L, the load resistor, is to develop the output signal, E_O, as well as limit plate current to a safe value. Changes in grid voltage cause changes in plate current. The changing plate current in R_L develops the output voltage.

19. (c) increases. — The voltage drop across R_L is directly proportional to the plate current. Increasing plate current increases the voltage drop across R_L, and vice versa.

20. 270 volts and 30V. — The drop across R_L is equal to 9×10^4 ohms $\times 3 \times 10^{-3}$ amperes, or 270 volts. The plate voltage E_b is equal to 300 volts — 270 volts, or 30 volts.

21. C_{pk} represents the plate-to-cathode interelecrode capacitance, C_{gk} represents the grid-to-cathode interelectrode capacitance and C_{gp} represents the grid-to-plate interelectrode capacitance.

22. The grid-to-plate interelectrode capacitance generally has the most undesirable effect on the operation of the triode.

23. (a) grid-to-plate interelectrode capacitance. — The screen grid shields the grid from the plate.

PRACTICE EXERCISE SOLUTIONS (Continued)

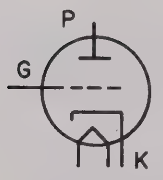
24. (b) positive with respect to the cathode. — The screen grid is normally operated at a potential near or equal to that of the plate.

25. Yes — The screen is positive and therefore attracts electrons. Since it is a wire structure, it attracts only a small number of electrons to form the screen grid current. Most of the electrons pass through the screen grid on to the plate.

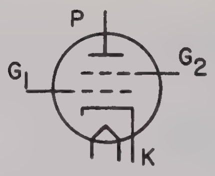
26. The screen grid has greater control over plate current than the plate has in a tetrode tube.

27. The suppressor grid repels the secondary electrons emitted from the plate. Generally, the suppressor grid is connected to the cathode.

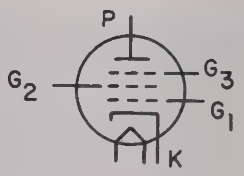
28. The schematic symbols for the triode, tetrode and pentode are as shown below.



TRIODE



TETRODE



PENTODE

29. Special electrodes form the electrode stream into thin sheets or beams. The resultant charge of the beam is high enough to repel secondary electrons back into the plate.

30. No — The screen is in the shadow of the control grid and fewer electrons strike it, thus reducing screen current.

31. There are seven active elements in a pentagrid tube: plate, cathode and five grids.

32. A hard tube is a tube that is highly evacuated and is commonly called a vacuum tube. The soft tube has a small amount of gas placed in it after evacuation. This type of tube is called a gas tube.

33. True — In general, the closer the spacing, the higher the mu.

34. In a variable-mu tube the grid wires are unevenly spaced, as shown in Figure 30.

35. If the peak heater-cathode voltage rating of a vacuum tube is exceeded, the insulation between the heater and cathode can be damaged, resulting in a short.

36. The maximum plate dissipation specifies the amount of heat that the plate of a tube can safely dissipate.

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1049A
EXAMINATION CHECK SHEET

1049A

1. B - IN A TRIODE VACUUM TUBE, THE PRIMARY PURPOSE OF THE GRID IS TO -- CONTROL THE FLOW OF ELECTRONS.
By varying the voltage on the grid, the electron flow from the cathode to the plate can be varied.

2. B - UNDER NORMAL OPERATING CONDITIONS, THE CONTROL GRID IS -- MADE NEGATIVE WITH RESPECT TO THE CATHODE.
Increasing the negative grid voltage decreases plate current and vice versa.

3. C - THE PLATE OF A TUBE IS GENERALLY MADE -- POSITIVE WITH RESPECT TO THE CATHODE.
The plate is made positive so it will attract electrons from the space charge.

4. D - THE DC DIFFERENCE OF POTENTIAL BETWEEN THE GRID AND CATHODE IS CALLED -- THE GRID BIAS.
The dc voltage between the grid and cathode is generally designated as E_c. The grid supply voltage is generally designated as E_{cc}.

5. A - THE TUBE EMPLOYED IN FIGURE 6 IS -- INDIRECTLY HEATED.
The symbol in Figure 6 shows a separate cathode so the tube is indirectly heated. Figure 5 shows a directly heated tube.

6. D - IN THE CIRCUIT OF FIGURE 8, WHEN WE MAKE THE GRID MORE NEGATIVE, -- THE PLATE CURRENT DECREASES.
Making the grid more negative increases the repelling force of the grid and plate current decreases.

7. C - SINCE THE GRID IN A TRIODE IS CLOSER TO THE CATHODE THAN THE PLATE IS, THE GRID -- HAS MORE CONTROL OVER PLATE CURRENT THAN THE PLATE.
The element closest to the cathode has the greatest control over plate current.

8. B - THE FUNCTION OF R_L IN THE CIRCUIT OF FIGURE 11 IS TO -- DEVELOP THE OUTPUT SIGNAL.
Plate current flowing through load resistor R_L develops the output signal.

9. B - THE SCREEN GRID IN A TETRODE OR PENTODE -- REDUCES THE CONTROL GRID-TO-PLATE CAPACITANCE.
In addition to reducing interelectrode capacitance, the screen grid provides a constant current characteristic.

10. B - IN THE BEAM POWER TUBE, SECONDARY ELECTRONS ARE PREVENTED FROM FLOWING FROM THE PLATE TO THE SCREEN GRID BY THE -- SPACE CHARGE.
The heavy beams of electrons form a highly negative space charge which repels the secondary electrons, forcing them back into the plate.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1049A

Example: Most windows are made of
A. wood. B. steel. C. glass. D. iron.

A ☐
B ☐
C ■
D ☐

1. A ☐ B ☒ C ☐ D ☐
In a triode vacuum tube, the primary purpose of the grid is to
(A) emit electrons. (B) control the flow of electrons. (C) shield the plate from the cathode. (D) prevent electrons from striking the cathode.

2. A ☐ B ☒ C ☐ D ☐
Under normal operating conditions, the control grid is
(A) made positive with respect to the cathode. (B) made negative with respect to the cathode. (C) at the same potential as the cathode. (D) at the same potential as the plate.

3. A ☐ B ☐ C ☒ D ☐
The plate of a tube is generally made
(A) negative with respect to the grid. (B) negative with respect to the cathode. (C) positive with respect to the cathode. (D) the same potential as the grid.

4. A ☐ B ☐ C ☐ D ☒
The dc difference of potential between the grid and cathode is called
(A) the space charge. (B) E_o. (C) E_{bb}. (D) the grid bias.

5. A ☒ B ☐ C ☐ D ☐
The tube employed in Figure 6 is
(A) indirectly heated. (B) directly heated. (C) a type that employs no heating element. (D) a tetrode.

6. A ☐ B ☐ C ☐ D ☒
In the circuit of Figure 8, when we make the grid more negative,
(A) the grid bias decreases. (B) the plate current increases. (C) E_{bb} decreases. (D) the plate current decreases.

7. A ☐ B ☐ C ☒ D ☐
Since the grid in a triode is closer to the cathode than the plate is, the grid
(A) is usually operated at a positive potential. (B) has less control over plate current than the plate. (C) has more control over plate current than the plate. (D) collects most of the electrons coming from the space charge.

8. A ☐ B ☒ C ☐ D ☐
The function of R_L in the circuit of Figure 11 is to
(A) develop the input signal. (B) develop the output signal. (C) limit grid current. (D) increase plate current.

9. A ☐ B ☒ C ☐ D ☐
The screen grid in a tetrode or pentode
(A) serves as the control grid in the pentode. (B) reduces the control grid-to-plate capacitance. (C) causes secondary electrons to move toward the plate. (D) prevents secondary emission.

10. A ☐ B ☒ C ☐ D ☐
In the beam power tube, secondary electrons are prevented from flowing from the plate to the screen grid by the
(A) control grid. (B) space charge. (C) cathode. (D) screen grid.

EXPERIMENT 3

VACUUM TUBE CIRCUITS - TRIODE VACUUM TUBE OPERATION

PARTS NEEDED

1 - Multimeter with Test Leads and Spring Adapters
1 - Partially Completed Design Console
1 - 1 MΩ Potentiometer with Bracket and Leads
1 - 9-Pin Miniature Tube Socket with Leads
2 - Tri-mounts
1 - 12AU7 Tube
1 - Silicon Diode
1 - 100 kΩ, 1/2 W, Resistor
1 - 10 µF, 50V, Electrolytic
17 - Modular Connectors
- No. 22 Solid Hookup Wire

OBJECTIVE

In this experiment you will investigate the dc action of a triode vacuum tube by observing how plate current and plate voltage are controlled by the grid voltage.

PROCEDURE

1. In this experiment you will be working with a medium-mu twin triode vacuum tube, the 12AU7. This tube consists of two separate triode sections sharing a common filament. The schematic diagram for the 12AU7 is shown in Figure 3-1A. The filament is designed for either 6 or 12 volt operation, by the use of the center-tap at pin 9, as shown in Figure 3-1B. We will use only one of the triode sections and the 6 volt filament arrangement, since the socket you pre-wired is set up only for 6 volt operation.

When working with vacuum tube circuits, much higher voltages are encountered than voltages for most transistor circuits. Thus, EXERCISE CARE so you do not come in contact with the +180 volt supply on the design console.

2. Set up the circuit of Figure 3-2, following the layout shown in Figure 3-3. Use the two tri-mounts to fasten the potentiometer bracket to the design panels. Make sure that the design console is turned off while setting up or changing the circuit. Align the wide spacing of the tube pins over the wide spacing between holes in the tube socket. While holding the socket, gently insert the tube. If any of the tube pins are bent, straighten them with your long-nose pliers.

3. Turn the shaft on R_2 completely clockwise. This will put maximum negative voltage on the grid of V_1. The circuit consisting of D_1, C_1 and R_2 forms a filtered half wave rectifier circuit to supply bias to the grid circuit of V_1.

4. Turn on the design console. You can leave the selector switch in either the 6 volt or 30 volt position, since the low voltage supply is not used. Set the voltage adjust control fully counterclockwise. Both sides of the filament should light.

5. Connect your multimeter to measure the grid voltage of V_1. Remember, the grid is negative with respect to the cathode. Connect the red lead to the cathode (ground) and the black lead to the grid of V_1. Adjust R_2 until the grid-to-cathode voltage is -15 volts.

With the grid-to-cathode voltage E_c equal to -15 volts, measure the plate-to-cathode voltage E_b. Remember, the plate is positive with respect to the cathode. Record the value of E_b in the chart of Figure 3-4 in the first space in the E_b column.

6. Now measure the supply voltage, which should be approximately 180 volts. Record the value here.

Plate Supply Voltage 200 volts dc

To calculate the plate current, I_b, determine the voltage drop across the plate load resistor R_1; and divide this voltage by the color coded value of R_1. For example, suppose the plate voltage is 180 volts and the plate supply voltage is 185 volts. With a 5 volt drop across R_1, the plate current would be:

$$I_b = \frac{E_{R_1}}{R_1} = \frac{5\,\text{V}}{100\,\text{k}\Omega} = \frac{5\,\text{V}}{1 \times 10^5} = 5 \times 10^{-5}\text{A (or } 50\ \mu\text{A).}$$

Enter your computed value of I_b in the chart of Figure 3-4.

7. Complete the chart of Figure 3-4 by setting the grid voltage to the values indicated, measuring and recording the voltage at the plate, and computing and recording the plate current. Use the same meter voltage range for all of the readings in this chart. If you switch to a lower voltage range, the loading effect of the meter will affect the circuit action. Your data should show that plate current is inversely proportional to grid voltage. That is, as the grid is made less negative, plate current increases. As plate current increases, the voltage drop across the load resistor increases, reducing the voltage at the plate.

8. Using the data from the chart of Figure 3-4, construct an I_b-E_c curve on the graph shown as Figure 3-5. Locate points which correspond to the various values of grid voltage and computed plate current. Connect the points with a smooth line.

Your completed graph should have the general appearance of that shown in Figure 3-6. However, since no two tubes are alike, the characteristic curve for each 12AU7 will be different. If you look in a tube manual, you will note that the curves appearing in the manual are labeled "average."

This completes the work of this experiment. Turn off the design console and dismantle the circuit.

CONCLUSION

Like the transistor, the vacuum tube is a variable resistance device. The internal resistance of the tube, and thus the plate current, depends upon the grid voltage. Your I_b-E_c curve in Figure 3-5 should show that the relationship between I_b and E_c is relatively linear over most of the range. When used as an amplifier, the tube would be biased in the center of this linear range.

NOTES

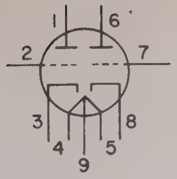


FIGURE 3-1A

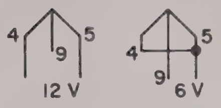


FIGURE 3-1B

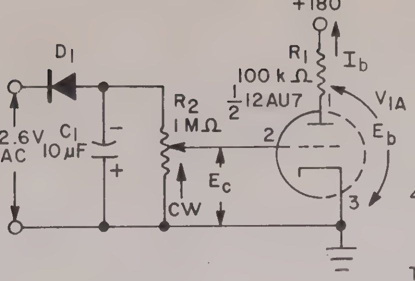
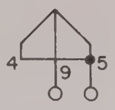


FIGURE 3-2



6.3 VAC
TUBE FILAMENT
CONNECTIONS
FOR 12AU7

Ec	Eb	Ib
−15 V	195	50μ
−12 V	190	100μ
−10 V	176	240μ
−8 V	155	450μ
−5 V	110	900μ
−3 V	75	1.25m
−2 V	55	1.45m
−1 V	40	1.6m
0 V	15	1.85m

FIGURE 3-4

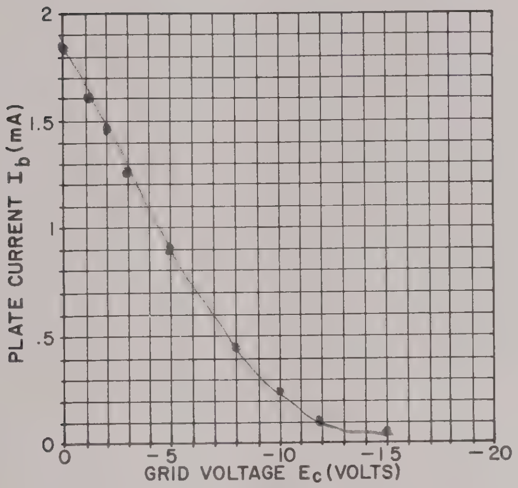


FIGURE 3-5

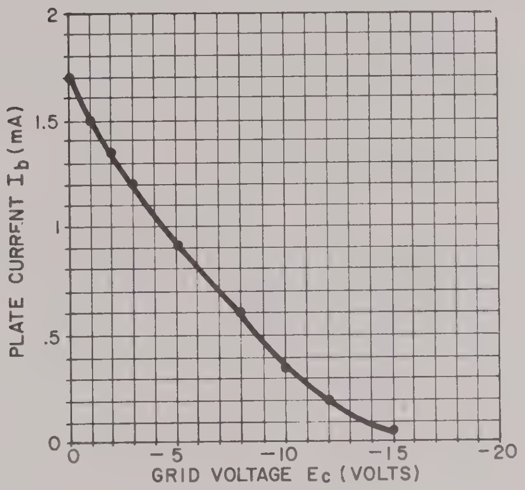


FIGURE 3-6

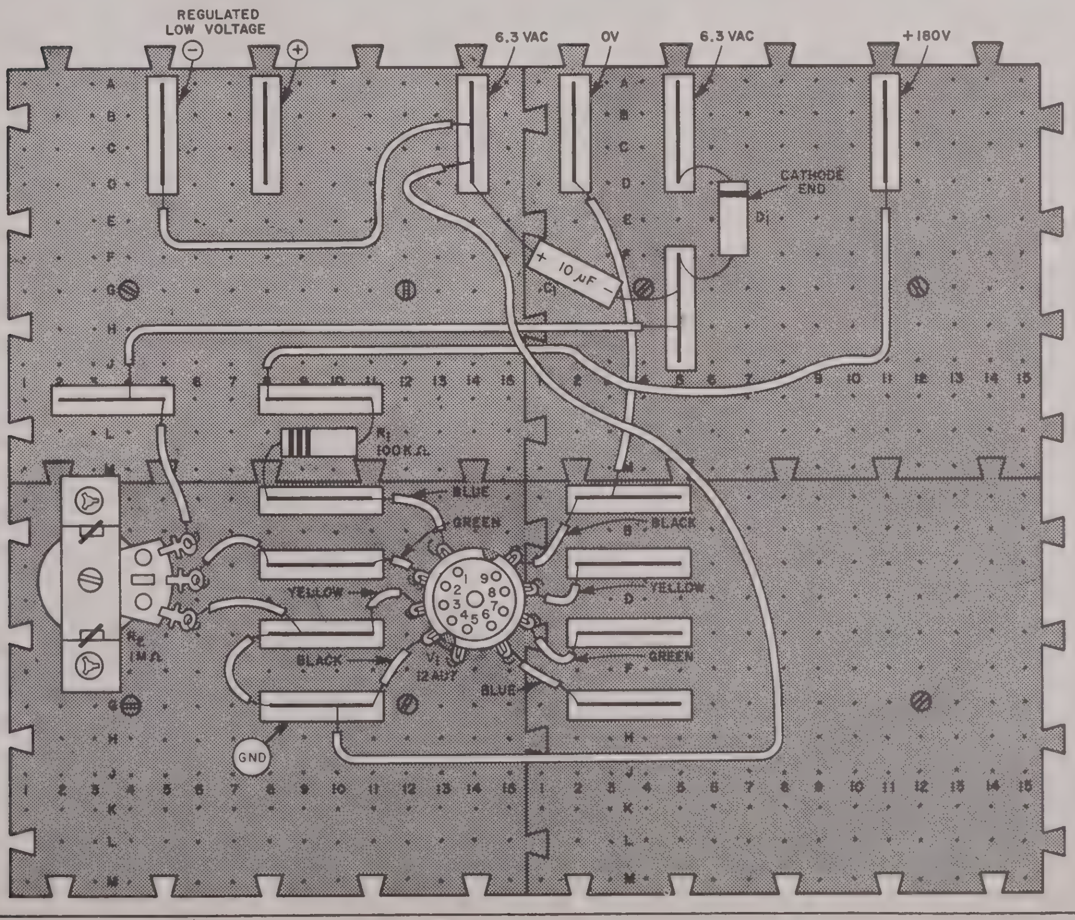


FIGURE 3-3

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9504-3A&B
EXAMINATION CHECK SHEET

NOTICE: To keep our lessons up-to-date, we add material to the texts from time to time, and make occasional changes in the examination questions. Therefore, when checking your answers with this check sheet, look at the code LETTER (A, B, C, etc.) on your examination sheet to determine which of the following groups of answers apply to the lesson which you have.

9504-3B

1. C - FOR PROPER OPERATION OF A VACUUM TUBE, -- THE GRID IS MADE NEGATIVE WITH RESPECT TO THE CATHODE.
To control plate current, the grid is made negative with respect to the cathode. The plate is made positive with respect to the cathode to attract the electrons on the cathode.

2. A - IN THE CIRCUIT OF FIGURE 3-2, WHEN THE GRID IS MADE MORE NEGATIVE, -- THE PLATE CURRENT DECREASES.
When the grid is made more negative, the plate current decreases due to the opposing effect of the grid.

3. D - REFERRING TO THE CIRCUIT OF FIGURE 3-2, SUPPOSE E_b = 85 VOLTS AND THE PLATE SUPPLY IS 180 VOLTS AS SHOWN. WHAT IS THE PLATE CURRENT? -- .95 mA.
The plate current is found by dividing the drop across R_1 by the value of R_1:

$$I_b = \frac{E_{R1}}{R_1} = \frac{180V-85V}{100K} = \frac{95 \text{ volts}}{100K} = \frac{95}{1 \times 10^{-5}} = 95 \times 10^{-5} = 950\ \mu A = .95 \text{ mA.}$$

4. C - IF THE SLIDER ON R_2 IN FIGURE 3-2 IS MOVED UPWARD, -- THE PLATE VOLTAGE INCREASES.
Moving the slider upward on R_2 increases the negative voltage on the grid, thus reducing the plate current and increasing the voltage at the plate.

5. B - DETERMINE THE GRID VOLTAGE THAT WILL CAUSE THE VOLTAGE AT THE PLATE OF THE TUBE IN FIGURE 3-2 TO BE HALF OF THE HIGH VOLTAGE SUPPLY. (HINT: FIRST FIND THE CURRENT THROUGH R_1 THAT CAUSES THE VOLTAGE ACROSS R_1 TO BE HALF OF THE SUPPLY VOLTAGE. THEN USE FIGURE 3-6 TO FIND THE GRID VOLTAGE NEEDED TO PRODUCE THAT CURRENT.) -- -5 VOLTS.
Half of the supply voltage, 180, is 90 volts, the drop across R_1 (E_{R1}). The current through R_1 is the plate current of the tube:

$$I_b = \frac{E_{R1}}{R_1} = \frac{90 \text{ volts}}{100 \text{ k}\Omega} = 0.9 \text{ mA.}$$

From the graph of Figure 3-6 when I_b is 0.9 mA, then E_C is -5 volts.

9504-3A

All explanations are the same as for 9504-3B except for that given below.

5. B - THE CONDITION THAT OCCURS WHEN PLATE CURRENT INCREASES NO FURTHER DUE TO A DECREASE IN GRID VOLTAGE IS CALLED -- SATURATION.
Saturation occurs when all the electrons in the space charge are attracted to the plate.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
9504-3B

1. A ☐ B ☐ C ☒ D ☐

For proper operation of a vacuum tube,
(A) the grid is made positive with respect to the cathode. (B) the cathode is made positive with respect to the plate. (C) the grid is made negative with respect to the cathode. (D) the grid is made positive with respect to the plate.

2. A ☒ B ☐ C ☐ D ☐

In the circuit of Figure 3-2, when the grid is made more negative,
(A) the plate current decreases. (B) the grid current increases. (C) the cathode voltage decreases. (D) the plate supply voltage decreases.

3. A ☐ B ☐ C ☐ D ☒

Referring to the circuit of Figure 3-2, suppose E_b = 85 volts and the plate supply is 180 volts as shown. What is the plate current?
(A) 9.5 mA. (B) 8.5 mA. (C) 95 µA. (D) .95 mA.

4 A ☐ B ☐ C ☒ D ☐

If the slider on R_2 in Figure 3-2 is moved upward,
(A) the plate current increases. (B) the plate voltage decreases. (C) the plate voltage increases. (D) the voltage drop across R_1 increases.

5. A ☐ B ☒ C ☐ D ☐

Determine the grid voltage that will cause the voltage at the plate of the tube in Figure 3-2 to be half of the high voltage supply. (Hint: First find the current through R_1 that causes the voltage across R_1 to be half of the supply voltage. Then use Figure 3-6 to find the grid voltage needed to produce that current.)
(A) -2.5 volts. (B) -5 volts. (C) -7.5 volts. (D) -10 volts.

6. A ☐ B ☐ C ☐ D ☐

7. A ☐ B ☐ C ☐ D ☐

(This exam contains only 5 questions.)

8. A ☐ B ☐ C ☐ D ☐

9. A ☐ B ☐ C ☐ D ☐

10. A ☐ B ☐ C ☐ D ☐

PRINTED IN USA

VACUUM TUBE CHARACTERISTICS

1052

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The mixer preamplifier shown above employs six dual triodes in the various circuits. The linearity offered by triodes makes them especially suited to low-level audio applications.

Courtesy Lear Siegler Inc.
Bogen Communications Division

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> *Things don't turn up in this world until somebody turns them up.*
>
> *—Garfield*

VACUUM TUBE CHARACTERISTICS

Have you noticed that the more you learn about things, the deeper your interest generally becomes? Perhaps you have already found this to be true for electron tubes. You probably know that they are important parts of television and radio receivers, and other electronic equipment. But only when you begin to study electronics do you find that the tubes themselves are very interesting devices.

A fast way to learn a lot about electron tubes is to look at the graphs or "curves" that picture their operation. Neither word descriptions nor mathematical equations are as good as graphs to give a picture of what happens in the circuit of an electron tube.

In tube circuits, a change of input voltage usually causes more than one thing to change in the circuit. The changes can be shown with curves. These curves for tube circuits are called CHARACTERISTIC CURVES. They tell us a great deal about a tube or tube circuit. A true understanding of tube characteristic curves is a powerful tool. With this tool, guesswork is replaced with exact knowledge — a practical, usable type of knowledge.

In their published data, tube manufacturers give some tube characteristics in the form of curves, but list other characteristics, called tube factors, merely as values. This lesson explains both kinds of characteristics.

TYPES OF CHARACTERISTIC CURVES

There are several types of tube characteristic curves. Those which show the operation of the tube without regard to the effects of other circuit components are **STATIC CHARACTERISTIC CURVES**. Common examples are curves that show the relationship between the plate voltage and plate current, and those that show how grid voltage and plate current are related. When a characteristic curve shows the operation of a tube in a specific circuit, it is called a **DYNAMIC CHARACTERISTIC CURVE**.

PLATE CHARACTERISTIC CURVES

One of the most useful and commonly available curves published by tube manufacturers is the **PLATE CHARACTERISTIC CURVE**. It is obtained from corresponding sets of plate voltage and current values. The voltages of all the other tube electrodes are held constant for each curve.

Figure 1 shows the basic tube circuit for obtaining the static plate characteristic curve of a triode. The current supply for the heater is omitted to simplify the drawing, but must be included in any practical circuit. E_{cc} provides negative bias E_c for the grid of triode V_1. Positive voltage for the plate is obtained from the movable contact of R_1. This control changes the amount of the E_{bb} voltage that is applied to the plate of V_1. Meter MA indicates the plate current.

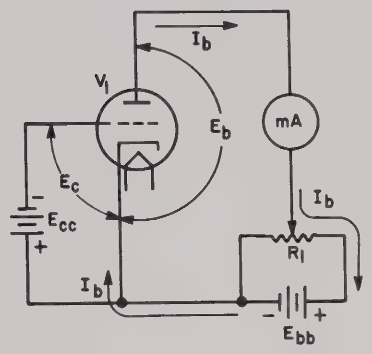


Figure 1

A circuit like that of Figure 1 can be used to provide the data needed to plot characteristic curves. However, most manufacturers provide curves for the various types of tubes, so it is not necessary to plot these curves yourself. Figure 2 is an example of a plate characteristic curve.

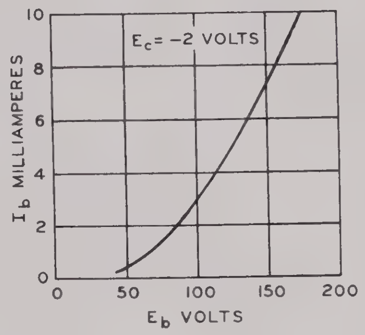


Figure 2

In plate characteristic curves, such as shown in Figure 2, it is standard practice to place the plate voltage scale horizontally along the bottom and the plate current scale vertically along the side. You can use this type of curve to find the exact plate current produced by any particular plate voltage within the range of the curve. This curve is commonly called an I_b-E_b curve because it shows the relationship between the plate current, I_b, and the plate voltage, E_b, for a given value of bias voltage, E_c.

On the graph of Figure 2, moving to the right corresponds to increasing plate voltage, while moving upward corresponds to an increase in plate current. As the curve starts at the bottom and swings upward to the right, it indicates that plate current increases as the plate voltage is increased. The curvature of the curve shows that I_b rises slowly at first as E_b increases steadily, and then rises more rapidly as higher values of E_b are reached. This shows that the change of plate current with change of plate voltage is not perfectly linear. An exactly linear relation between I_b and E_b would result in a straight line curve slanting upward at some angle.

The single I_b-E_b curve of Figure 2 shows the increase of I_b with E_b for only the indicated single grid bias value of —2 volts. To show the changes in plate current provided by varying BOTH the plate voltage and the grid voltage, we must use a **FAMILY OF CURVES**, as shown in Figure 3. Each curve has been drawn with the grid voltage held at the values indicated at the upper ends of the curves.

The curves in Figure 3 are similar to each other except for their positions. Each shows an increase in plate current with an increase of plate voltage.

Making the grid more negative shifts the curve toward the right on the graph. That is, when the grid is more negative, a higher plate voltage is needed to produce a given plate current. Also, at any given plate voltage, the plate current decreases if the grid is made more negative.

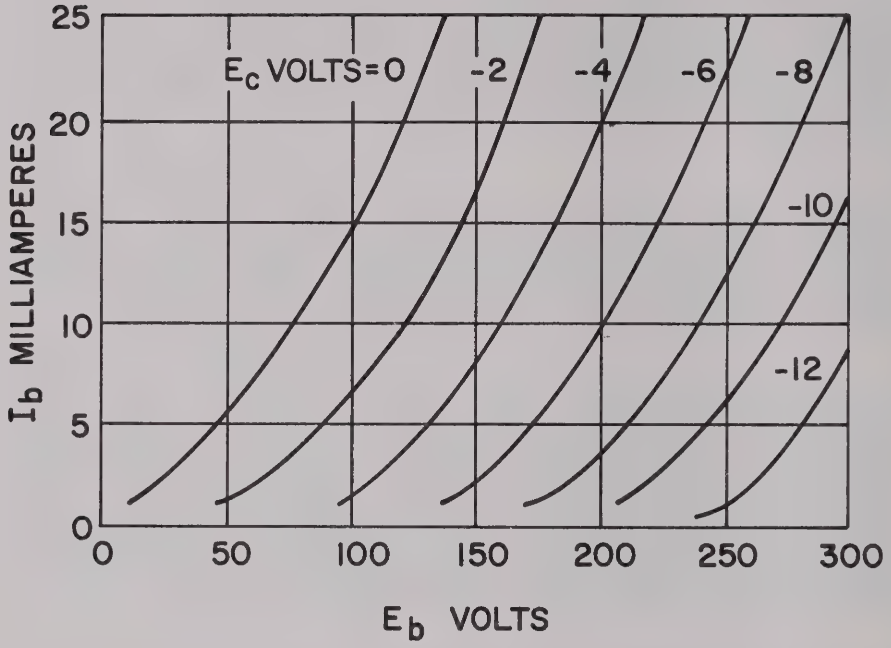


Figure 3

For example, Figure 3 shows that when E_b is 200 volts, I_b is 20 mA if the grid is at —4 volts. But, if grid voltage E_c is increased to —6 volts, plate current falls to 10 mA. You find this lower value of I_b by moving down the E_b = 200 volts line to where it touches the E_c = —6 volts curve, then left to the I_b scale.

At the same plate voltage of 200 volts, if grid voltage E_c is further increased to —8 volts, the plate current decreases to about 3.8 mA.

A single curve like that of Figure 2 shows the effect on plate current produced when only the plate voltage changes. The grid voltage is held constant in obtaining the values to plot this curve. However, in most circuits, both the plate and grid voltages change at the same time. They both affect the plate current and, as shown in Figure 3, a family of curves indicates plate current can be changed by varying either the plate or grid voltage. Thus, the family of curves tells more about the tube action than does the single curve.

The steep rise of the curves of Figure 3 shows that a given change of plate voltage causes the plate current to change a large amount. This is typical of triodes: one type of triode is represented by Figure 3. However, for greatest voltage amplification the plate current should be controlled mainly by the control grid, and the plate voltage should have little effect on the plate current.

The curves of Figure 3 are typical for triode tubes. Curves for tetrodes and pentodes are somewhat different. In tetrode and pentode tubes, the screen grid electrically separates the control grid and plate. As a result, above a certain level the plate voltage has almost no effect on the plate current. Because the screen grid is normally held at a constant potential, only the changes of control grid voltage cause large changes of plate current.

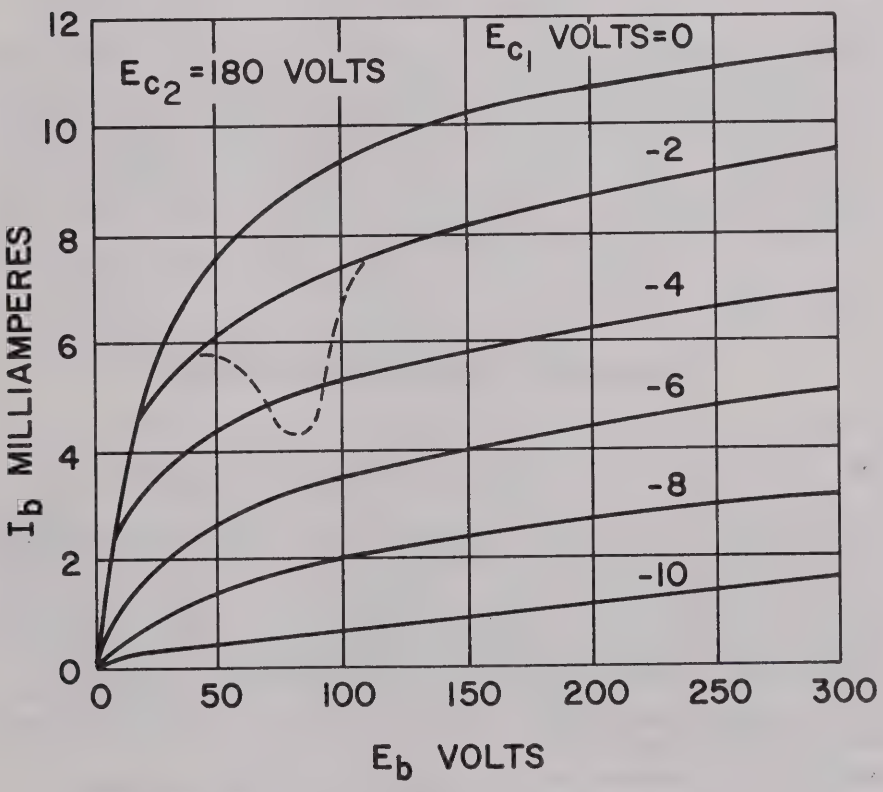


Figure 4

Figure 4 shows a family of I_b-E_b curves for a typical pentode tube. As indicated at the upper left, these curves have been plotted with 180 volts applied to the screen grid. A higher screen voltage would raise all the curves to higher positions on the graph. Notice that these curves have only small vertical slopes over most of their ranges. This shows that plate current varies only slightly for E_b values greater than about 50 volts, in this example. This action gives the pentode a CONSTANT CURRENT CHARACTERISTIC. Normally, we operate a pentode so that the plate voltage remains in the region where the slope of the curve is small. The plate curves for a beam power tube are also similar to those of Figure 4.

The I_b-E_b curves of a tetrode are like those of Figure 4, except that each curve has a dip near the left end, as shown by the dotted line indicated for one of the curves. For a tetrode operated with the values shown in Figure 4, the plate curves dip in the region between about 50 and 100 volts. For example, the $E_c = -2$ volts curve would dip as indicated by the dashed line. A tetrode is normally operated in the E_b range above the dip region.

Tetrodes have greater amplification than triodes, and were commonly used before pentodes and beam power tubes were developed. The dip in the tetrode plate curves limits the range of plate voltage over which this type of tube can be operated. Therefore, a pentode or a beam power tube is better than a tetrode when a large swing of plate voltage is required. Generally, tetrodes are used where very high power is needed. At high voltages they are less apt to break down than some other types.

TRANSFER CHARACTERISTICS

TRANSFER CHARACTERISTIC CURVES show the changes of current or voltage of one electrode caused by the voltage or current variations of another electrode. One type published by tube manufacturers is the **PLATE CURRENT-CONTROL GRID VOLTAGE (I_b-E_c) CHARACTERISTIC CURVE**. Figure 5 shows the I_b-E_c curve for a typical triode. This curve shows directly how the plate current, I_b, changes with variations of the grid voltage, E_c. As indicated at the upper left, plate voltage E_b is held at 250 volts in this example. The point at which the curve meets the lowest or zero I_b line is called the cutoff point. The grid voltage value at this point is called the **CUTOFF GRID BIAS.**

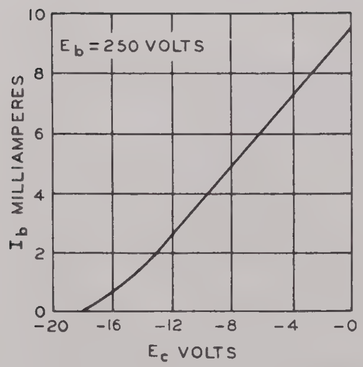


Figure 5

A family of I_b-E_c curves can be made by drawing a curve for each of several different plate voltages. When the plate voltage is decreased, the grid cuts off the plate current at a lower value of E_c. Thus, for the tube represented by Figure 5, the curves for plate voltages less than 250 volts would be located to the right of the curve shown. Curves for higher plate voltages would be located farther to the left.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TYPES OF CHARACTERISTIC CURVES

PLATE CHARACTERISTIC CURVES

1. What is the difference between a static and a dynamic characteristic curve?

2. A curve that shows plate current values for given plate voltages is a (a) plate characteristic curve, (b) grid characteristic curve, (c) grid-plate characteristic curve.

3. According to Figure 2, when the plate voltage $E_b = 100$ volts and the grid voltage $E_c = -2$ volts. the plate current I_b will be about (a) 2 mA, (b) 3 mA, (c) 4 mA.

4. The curve of Figure 2 shows that, at the given E_c value, an increase of plate voltage causes plate current to (a) increase, (b) remain constant, (c) decrease.

5. Suppose you are using a tube of the type represented by the curve of Figure 2 in an amplifier circuit. From the curve, you can see that, if you apply —2 volts to the grid and 65 volts to the plate, the plate current will be (a) 0.5 mA, (b) 1.0 mA, (c) 2.0 mA.

6. The curvature of the I_b-E_b curve in Figure 2 shows that I_b increases linearly with E_b. True or False?

7. What is the advantage of a family of plate curves over a single curve?

8. When you study the graph of Figure 3 to see how the tube type represented operates, you find that a higher plate voltage is needed to produce a given plate current when the grid is (a) more negative, (b) less negative, (c) positive.

9. Examining the plate family in Figure 3, you find that, at a given plate voltage, plate current increases if you make the grid (a) more negative, (b) less negative.

10. When you see an I_b-E_b curve that rises steeply, you know that, in the tube type represented, a given change of plate voltage causes the plate current to (a) remain nearly constant, (b) change by a small amount, (c) change by a large amount.

11. Amplification is greatest when the plate voltage affects the plate current (a) only slightly, (b) a large amount.

12. In tetrode and pentode tubes, the control grid and plate are separated electrically by the (a) screen grid, (b) cathode, (c) filament.

13. In a tetrode or pentode, the plate voltage has very little effect on plate current. True or False?

14. If you operate a tube of the type represented in Figure 4 so that its plate voltage is greater than 100 volts, the change of plate current with plate voltage is (a) large, (b) small, (c) zero.

15. Suppose you are using a tube of the type represented in Figure 4 in an audio amplifier. With $E_b = 150$ volts, and $E_{c2} = 180$ volts and the control grid voltage $E_{c1} = -2$ volts, what is the plate current?

16. With the tube of Exercise 15 operated as explained, suppose you increase E_{c1} to -6 volts. What is the plate current?

Figure 6 shows an I_b-E_c transfer curve for a pentode. Compared with the triode curve of Figure 5, the pentode's plate current varies over a wider range, even though its control grid varies over the narrower range of only 8 volts. Notice that both the plate voltage, E_b, and the screen grid voltage, E_{c2}, are indicated near the curve of Figure 6. If E_{c2} were higher, the curve would be farther to the left; it would be farther to the right if E_{c2} were lower. Changes of E_b also change the location of the curve, although the amount of shift is very slight. Because of this, families of I_b-E_c curves for pentodes and beam power tubes are published with the curves drawn for different screen voltages, rather than for different plate voltages.

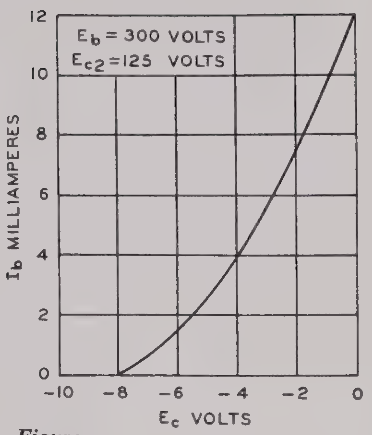


Figure 6

As a rule, the I_b-E_c curves do not include the positive region of grid voltage. This is true because most tube applications do not require that the grid be driven positive with respect to the cathode.

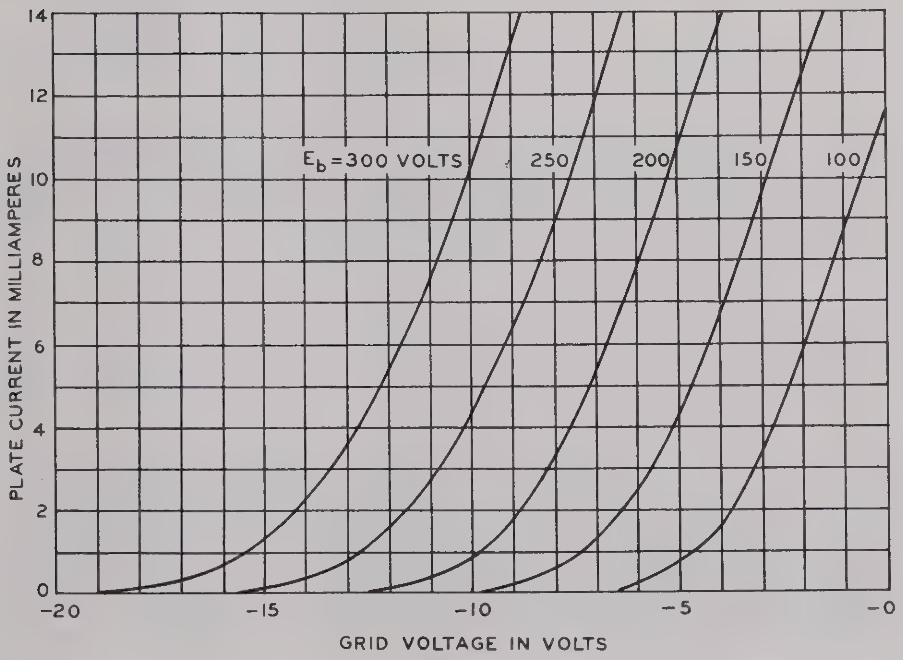


Figure 7

A family of I_b-E_c curves for a typical triode tube is shown in Figure 7. Here, a curve is drawn for each of five plate voltages. Again, the curves are similar. Each has a linear and a nonlinear part. Each has a plate-current cutoff point on the zero I_b line, and as the plate voltage increases, the negative bias required to cut off plate current also increases.

The 6AR11 Compactron tube shown on the left contains two pentode sections equivalent to the two separate tubes shown at the right.
Courtesy General Electric Co.
Tube Department

For any given bias voltage, the curves show that an increase in plate voltage causes an increase in plate current. For example, when the grid bias is —6 volts, 150 volts on the plate produces plate current of 2.5 mA, and a plate voltage of 200 volts produces 8 mA of plate current.

From Figure 7, you can see that the grid has a greater control over plate current than the plate has. For example, the curve for $E_b = 150$ volts shows that plate current equals 6.8 mA when $E_c = -4$ volts. If the plate voltage is increased to 200 volts with no change of E_c, the plate current increases to 13.7 mA. We can bring the plate current back to 6.8 mA by increasing the grid voltage to —6.4 volts. In this example, the change of grid voltage is 2.4 volts, while the change of plate voltage is 50 volts to produce the same change in plate current. That is, a change of only 2.4 volts on the grid has as much effect on the plate current as a change of 50 volts on the plate.

In general, the grid transfer family and the plate family of characteristic curves give the same information in somewhat different forms. The grid transfer family gives the plate current for small differences of grid voltage and a number of different plate voltages. The plate family gives the plate current for various values of plate voltage and a number of different grid voltages. These curves show the action of the tube itself, without reference to a particular practical circuit. You will see in later parts of this lesson how these curves are used with specific circuits.

TUBE FACTORS

Tube factors are numerical ratings that describe the traits and abilities of a tube. They provide a means of comparing tubes, and help to determine whether the tubes are suitable for particular applications. The behavior of the plate current in a vacuum tube depends upon the design of the tube. The separation between the electrodes, the shape and size of the electrodes, and other physical details all determine the effects of the applied voltages, and these effects are expressed by the tube factors.

Three primary factors which summarize tube action are the amplification factor, the transconductance and the plate resistance. Each of these is explained in the following pages.

Amplification Factor

The **AMPLIFICATION FACTOR (μ)** is a number that tells us how effective the control grid is compared to the plate in controlling plate current. For example, an amplification factor of 15 means that the grid is 15 times as effective as the plate in producing current changes in the plate circuit. The amplification factor is the ratio of the change in plate voltage to the change in grid voltage that produced it, when the plate current is held constant. Suppose a grid voltage change of 2 volts causes the plate voltage to change 30 volts when the plate current is held constant at 5 mA. The amplification factor is calculated by dividing the plate voltage change by the grid voltage change. Thus, in this example the amplification factor is equal to 30 ÷ 2, or 15.

The amplification factor is represented by the Greek letter μ, or the word mu, both of which are pronounced mew. Specifically, the amplification factor is defined as the result of dividing a small change in plate voltage by the smaller change in control grid voltage required to maintain the same level of plate current. It is assumed that all other electrode voltages remain constant. Expressed as an equation:

$$\mu = \frac{\Delta E_b}{\Delta E_c} \text{ with } I_b \text{ constant} \qquad (1)$$

where: Δ (delta) means a small change of,

E_b is the plate voltage in volts, and

E_c is the grid voltage in volts.

The value of μ is a pure number indicating a ratio without any units. It simply shows how much more effective the grid is than the plate in regulating plate current. The value of μ specified by the tube manufacturer is generally an average value and is determined for typical operating conditions.

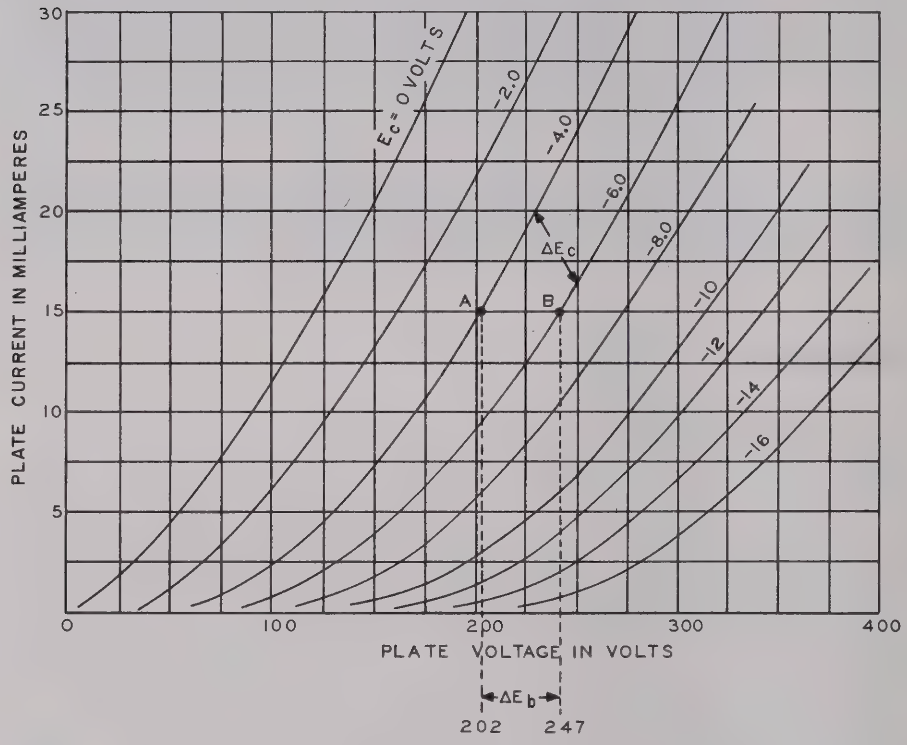


Figure 8

Figure 8 shows the plate characteristic curves for a typical medium μ triode. Let's determine the value of μ by using these curves. As mentioned earlier, the value of plate current must be held constant to determine μ. Suppose that we fix the plate current at 15 mA. Thus, any point on the 15-mA line represents a constant value of plate current. To determine μ, we change grid voltage and determine the resultant change in plate voltage. Let's change the grid voltage from —4 to —6 volts.

To find the plate voltage at a grid voltage of —4 volts, locate the intersection of the —4 curve and the 15-mA line — point A in Figure 8. From this point, drop down to the plate voltage scale, as shown by the dashed line. The plate voltage at this point is approximately 202 volts.

Use the same procedure to determine the plate voltage at a grid voltage of —6 volts. Point B is the intersection of the —6-volt curve and the 15-mA line. Following this point down to the plate voltage scale indicates a value of 247 volts.

Thus, when the grid voltage changes from —4 to —6 volts, the plate voltage changes from 202 to 247 volts. The change in grid voltage (ΔE_c) is 6 — 4, or 2 volts, and the change in plate voltage (ΔE_b) is 247 — 202, or 45 volts. Substituting these values into Equation 1 to determine μ yields:

$$\mu = \frac{\Delta E_b}{\Delta E_c} = \frac{45}{2} = 22.5$$

To determine the value of μ from characteristic curves, choose a value of plate current and grid voltage near the point where the tube is to operate. This is necessary because the value of μ will vary somewhat, depending upon the point on the curves where it is determined. The manufacturer's specification for μ is an average value.

Generally, triode tubes are classed as low, medium or high mu. A low-mu triode is one in which the amplification factor is less than 10. Medium-mu triodes have a mu ranging from 10 to about 50. In high-mu triodes, the mu is anywhere from about 50 to about 100. Because the control grids of pentodes and beam power tubes have much more control of the plate current than the grid in the triode does, their amplification factors range all the way from a few hundred to several thousand. Transconductance is of much greater importance with these tubes, and the mu is not usually listed in the manufacturer's literature.

Transconductance

Changing the control grid voltage of a tube causes the plate current to change. The tube factor that expresses the change in plate current produced by a change of grid voltage is called the **TRANSCONDUCTANCE** or **MUTUAL CONDUCTANCE**, represented by the symbol g_m. Transconductance is the term used to indicate the amount of control that a tube's control grid has on the plate current when the plate voltage is held at a constant value.

Since conductance is the opposite of resistance, we use the **MHO** as the unit of transconductance. (Mho is ohm spelled backward.) The SIEMENS is another unit used for transconductance and is the same as the mho.

A transconductance of one mho results when a change of grid voltage of one volt changes the plate current by one ampere. However, plate current changes are normally in the milliampere range, making the transconductance equal to only a small fraction of a mho. Therefore, we commonly express transconductance by using the smaller unit, MICROMHO, which equals one-millionth of a mho (10^{-6} mho). If the unit SIEMENS is used, the microsiemens would be used in place of the micromho.

Transconductance is the ratio of the change in plate current to the change in grid voltage that produced it, when the plate voltage is held constant. In equation form:

$$g_m = \frac{\Delta I_b}{\Delta E_c} \text{ with } E_b \text{ constant} \qquad (2)$$

where: g_m is the transconductance in mhos,

ΔI_b is a small change in plate current in amperes, and

ΔE_c is a small change in grid voltage in volts.

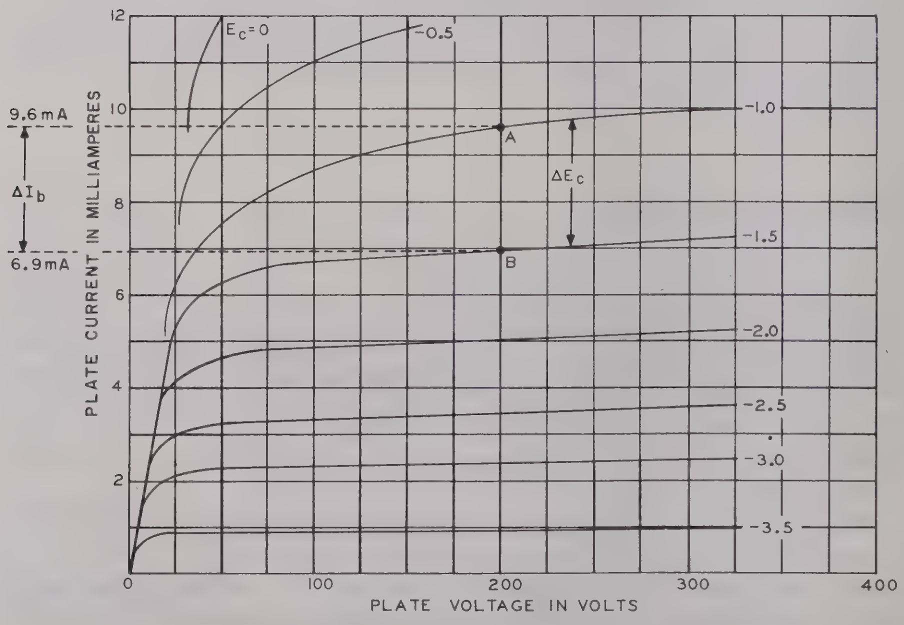


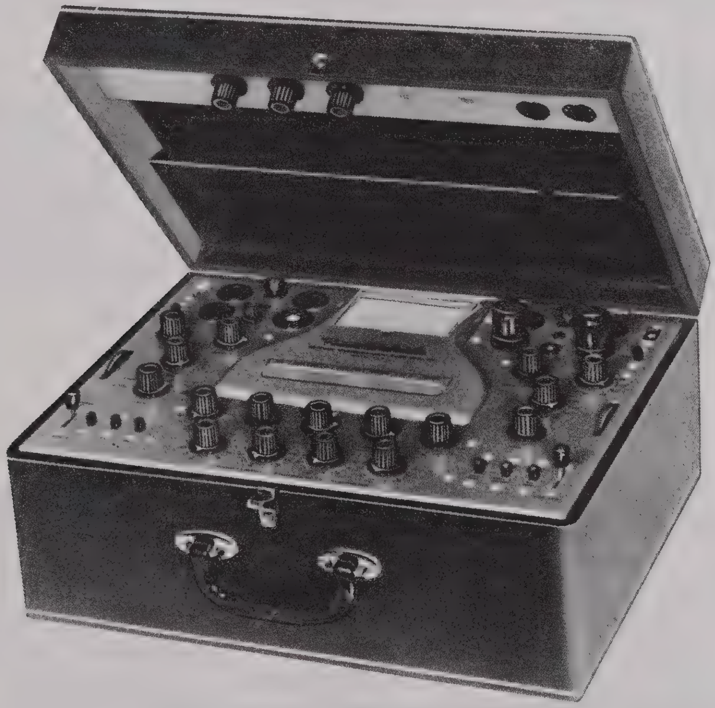
Figure 9

Whenever you use this equation, the transconductance will be in mhos if ΔI_b is in amperes. The transconductance will be in micromhos if I_b is in microamperes.

As an example, assume that a grid voltage change of 0.5 volt causes the plate current to change by 2 milliamperes. This is a current change of 2000 microamperes. Using these values in Equation 2, we have:

$$g_m = \frac{\Delta I_b}{\Delta E_c} = \frac{2000}{0.5} = 4000 \text{ micromhos.}$$

As with μ, transconductance can be determined from the characteristic curves. Figure 9 shows the characteristic curves for a typical pentode. To determine transconductance, the plate voltage is held constant. Grid voltage is then varied and the resultant change in plate current determined. Let's assume a constant plate voltage of 200 volts, and vary the grid voltage from —1 to —1.5 volts.



This tube tester measures the quality of a tube by measuring its transconductance.

Courtesy Heath Company

Point A in Figure 9 is the intersection of the —1-volt E_c curve and the 200-volt E_b line. Following the dashed line over the plate current scale shows a plate current of approximately 9.6 mA. Moving down on the 200-volt E_b line to maintain a constant E_b results in a plate current of approximately 6.9 mA at the —1.5-volt E_c curve, point B.

The change in grid voltage is therefore 1.5 — 1, or .5 volt, and the change in plate current is 9.6 — 6.9, or 2.7 mA. Substituting these values into Equation 2 results in a transconductance of:

$$g_m = \frac{\Delta I_b}{\Delta E_c} = \frac{2.7 \times 10^{-3} \text{ amperes}}{.5 \text{ volt}} = 5.4 \times 10^{-3} \text{ mhos,}$$

or 5400 micromhos.

As with μ, the value of g_m varies, depending upon the point on the curves where it is determined. The change in E_c should be as small as possible. Large changes in E_c result in inaccurate readings.

The transconductance of a tube is an important tube factor. It is the most commonly used of all the factors, especially when working with pentodes. In general, a tube with higher transconductance is capable of furnishing greater signal output than a tube with lower transconductance. The transconductances of the various tubes used in communications, entertainment and industrial equipment range in value all the way from about 100 micromhos to between 20 and 30 thousand micromhos.

Plate Resistance

The third major tube factor is the **DYNAMIC** or **AC PLATE RESISTANCE**, denoted by the symbol r_p. Dynamic plate resistance indicates the result of dividing a small change in plate voltage by the change it produces in the plate current, while the grid voltage is kept constant.

Dynamic plate resistance can be expressed by the equation:

$$r_p = \frac{\Delta E_b}{\Delta I_b} \text{ with } E_c \text{ constant} \tag{3}$$

where: r_p is the dynamic plate resistance in ohms,

ΔE_b is a small change in plate voltage, and

ΔI_b is a small change in plate current in amperes.

The grid voltage remains constant.

Although dynamic plate resistance, like μ and g_m, is given by the manufacturer, it can also be determined from the plate characteristic curves. Figure 10 shows the plate characteristics for a triode. The procedure for determining dynamic plate resistance follows.

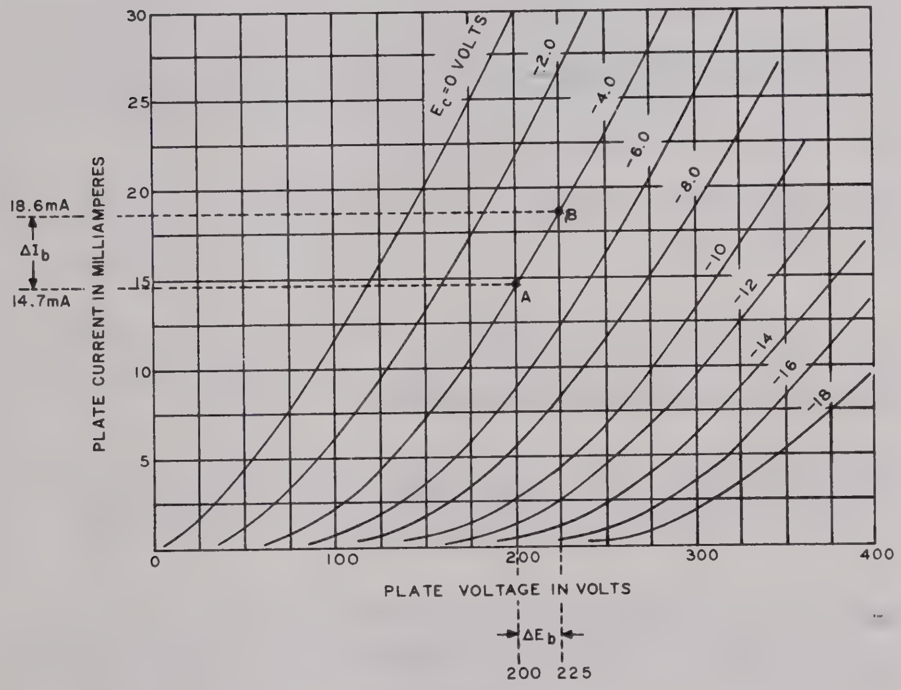


Figure 10

To determine dynamic plate resistance, the grid voltage is held constant, the plate voltage is varied, and the resultant change in plate current is determined. Let's hold the grid voltage constant at —4 volts and vary the plate voltage from 200 to 225 volts. As shown in Figure 10, point A is the intersection of the 200-volt E_b line and the —4-volt E_c curve. The plate current at this point is approximately 14.7 mA. Point B shows the intersection of the 225-volt E_b line and the —4-volt E_c curve. The plate current at this point is 18.6 mA.

The change in E_b is therefore 225 — 200, or 25 volts, and the change in I_b is 18.6 — 14.7, or 3.9 mA. Substituting these values into Equation 3 yields a plate resistance of:

$$r_p = \frac{\Delta E_b}{\Delta I_b} = \frac{25 \text{ volts}}{3.9 \times 10^{-3} \text{ amperes}} = 6.41 \times 10^3 \text{ ohms},$$

or approximately 6.4 kΩ.

For best accuracy, the changes in E_b should be kept as small as possible and should be taken close to the point where the tube is operating. The value of r_p varies, depending upon where the changes are taken.

Another type of plate resistance is also used at times. This is called **STATIC** or **DC PLATE RESISTANCE**, designated by the symbol $\mathbf{r_b}$. It is found by dividing a single value of plate voltage by the associated value of plate current with a certain value of grid voltage. The dc plate resistance in ohms can be calculated by using the equation:

$$r_b = \frac{E_b}{I_b} \tag{4}$$

As an example, if a tube produces a plate current of 5 mA when the plate voltage is 250 volts at a certain grid voltage,

$$r_b = \frac{E_b}{I_b} = \frac{250}{.005} = 50{,}000 \text{ ohms.}$$

The use of r_b is somewhat limited, compared to r_p. Therefore, whenever the term plate resistance is used, it will be assumed to mean r_p unless otherwise indicated.

Relationship between μ, g_m and r_p

The three tube factors — amplification, transconductance and plate resistance — are interrelated. Therefore, a change in any one may cause a change in either one or both of the others. Mathematically, amplification factor is equal to the product of transconductance and plate resistance. This can be seen by the relationships represented in Equations 1, 2 and 3. If we multiply g_m by r_p, it is the same as multiplying the ratios these terms stand for.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

- TRANSFER CHARACTERISTICS
- TUBE FACTORS
  - AMPLIFICATION FACTOR
  - TRANSCONDUCTANCE
  - PLATE RESISTANCE

17. The curve of Figure 5 shows that you can increase the plate current if you make the grid (a) less negative, (b) more negative.

18. What is the point called at which the transfer curves meet the zero plate current line in Figures 5, 6 and 7?

19. Compared with the plate voltage, the control grid voltage has (a) little effect on plate current, (b) no effect on plate current, (c) considerably more effect on plate current.

20. Although its form is different, the information you get from the ______________________________________ transfer family and ________________________ family of characteristic curves is the same.

21. The ratio of the change in plate voltage to the change in control grid voltage needed to maintain the same plate current is called the (a) transconductance, (b) amplification factor, (c) plate resistance.

22. What quantity is held constant when determining μ?

23. What is the value of μ when a change in grid voltage of 2 volts causes a change in plate voltage of 65 volts?

24. Is the value of μ the same at all points on a characteristic curve?

25. The result of dividing a change in plate current by the change in grid voltage that produced it (with E_b constant) is called the (a) transconductance, (b) amplification factor, (c) plate resistance.

26. Transconductance is normally specified in (a) ohms, (b) mhos, (c) micromhos.

27. What is the value of g_m when a change in E_c of 1 volt causes a change in I_b of 25 mA?

28. With E_c remaining constant, the dynamic plate resistance r_p is given by (a) $\Delta E_b/\Delta E_c$, (b) $\Delta E_b/\Delta I_b$, (c) $\Delta I_b/\Delta E_c$.

29. What is the basic unit of measurement for dynamic plate resistance?

30. Suppose a change in E_b of 35 volts produces a change in I_b of 10 mA when E_c is held constant at —3 volts. What is the value of r_p?

Therefore:

$$g_m \times r_p = \frac{\Delta I_b}{\Delta E_c} \times \frac{\Delta E_b}{\Delta I_b}$$

Since ΔI_b appears in the numerator of the g_m ratio and the denominator of the r_p ratio, multiplying these ratios cancels it from both to give:

$$g_m \times r_p = \frac{\Delta E_b}{\Delta E_c}$$

But $\Delta E_b/\Delta E_c$ is equal to amplification factor μ. Therefore:

$$\mu = g_m \times r_p. \tag{5}$$

Furthermore, if we divide both sides of Equation 5 by r_p, we have:

$$g_m = \frac{\mu}{r_p} \tag{6}$$

And, if we divide both sides of Equation 5 by g_m, we have:

$$r_p = \frac{\mu}{g_m} \tag{7}$$

Thus, if any two of the factors are known for a given tube, we can calculate the third by using Equation 5, 6 or 7.

LOAD RESISTOR

For a tube to be useful, it is usually connected so that its plate current passes through a load, such as resistor R_L in Figure 11. The actual load may be any of several devices, all of which are represented by R_L in this basic circuit. From a practical standpoint, this circuit contains the essential elements needed to employ a tube in a useful application (a tube filament supply is assumed present).

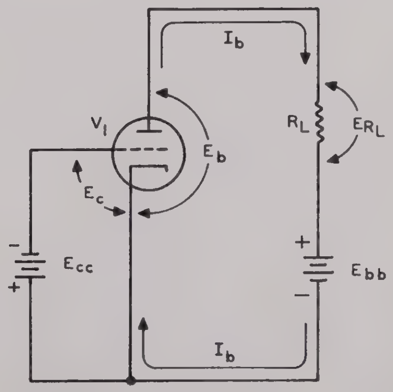


Figure 11

The load, R_L, is placed in between the tube and plate supply, E_{bb}. Therefore, V_1 plate current passes through the load. Because this current passes through the load, it is called the load current. This load current, passing through resistor R_L, causes a voltage drop across R_L. This voltage is labeled E_{R_L}. The varying voltage, E_{R_L}, serves as the output signal, or drives the load in some desired manner.

From the family of curves shown in Figure 10, we can determine what happens to the dc plate resistance of a tube when the grid voltage is changed. For example, with a plate voltage, E_b, of 300 volts, and a grid bias voltage, E_c, of -10 volts, the plate current, I_b, is about 13 mA. Using Equation 4, we find that the plate resistance for these conditions is:

$$r_p = \frac{E_b}{I_b}$$

$$= \frac{300}{.013}$$

$$= 23{,}000 \text{ ohms (approx.)}$$

Changing the grid bias voltage to -18 volts with $E_b = 300$ volts, I_b changes to about 2 mA. The dc plate resistance now becomes:

$$r_b = \frac{300}{.002}$$

$$= 150{,}000 \text{ ohms (approx.)}$$

Notice that making E_c more negative increases the dc plate resistance. With load R_L in the circuit of Figure 11, supply voltage E_{bb} divides between V_1 and R_L. Thus, E_{bb} is always equal to $E_b + E_{R_L}$. Looking at it another way, the load voltage, E_{R_L}, is always equal to $E_{bb} - E_b$, or the plate voltage, E_b, is always equal to $E_{bb} - E_{R_L}$. The smaller the negative grid voltage, the larger the plate current and load voltage, E_{R_L}, and the smaller the plate voltage, E_b. The larger the negative grid voltage, the smaller the plate current and load voltage, E_{R_L}, and the larger the plate voltage, E_b.

The changes of E_b and E_{R_L} represent operating or dynamic conditions in a practical circuit containing a load.

We can use families of characteristic curves to show the effects of the load by drawing slanted lines called LOAD LINES across the curves.

The grid voltage changes the plate current in the same general manner as before. However, with a load resistor in the circuit, the grid voltage affects the plate current less because this current is limited by R_L, as well as by the resistance of V_1.

LOAD LINES

A LOAD LINE shows how the supply voltage, E_{bb}, divides between the load and the tube. It also shows how E_b and E_{R_L} change as E_c and I_b change. The load line has no fixed association with tube factors or characteristics. It merely shows the effects of the load on the tube circuit. It indicates

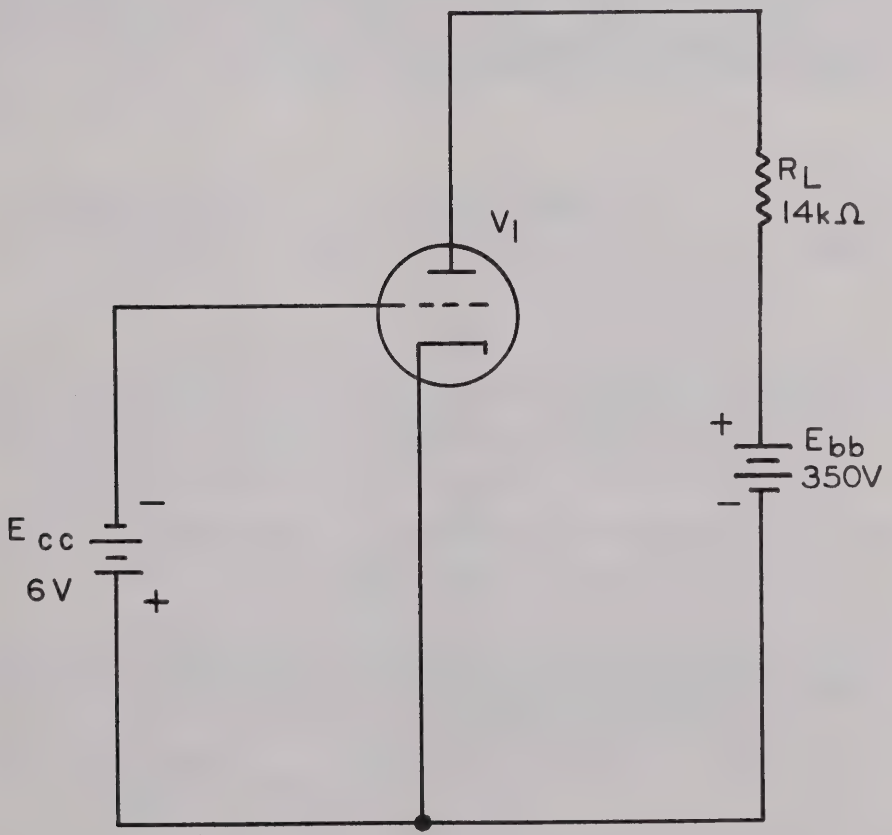


Figure 12

whether or not the load is the correct value for a given tube. A given load line shows the effects of only one load resistance, and other load lines must be drawn to determine the effects of other load resistances.

Plotting a Load Line

The load line, which shows how the supply voltage divides between the load and the tube, is simply a line drawn on the plate characteristic curves. A different line is drawn for each value of load resistance. To plot the load line, it is necessary to determine two points.

Let's draw the load line for the circuit of Figure 12. Assume that the characteristic curves of Figure 13 are for V_1 in Figure 12. To find the first load line point, assume that, in the circuit of Figure 12, V_1 is cut off. Under these conditions, V_1 plate current is zero, the voltage drop across R_L is zero and the entire plate supply voltage, 350 volts, appears across V_1. Thus, when I_b is 0, E_b is equal to E_{bb}. This set of conditions forms one point for the load line, the OPEN CIRCUIT POINT. This point, $I_b = 0$ and $E_b = 350$ volts, is labeled as the open circuit point in Figure 13.

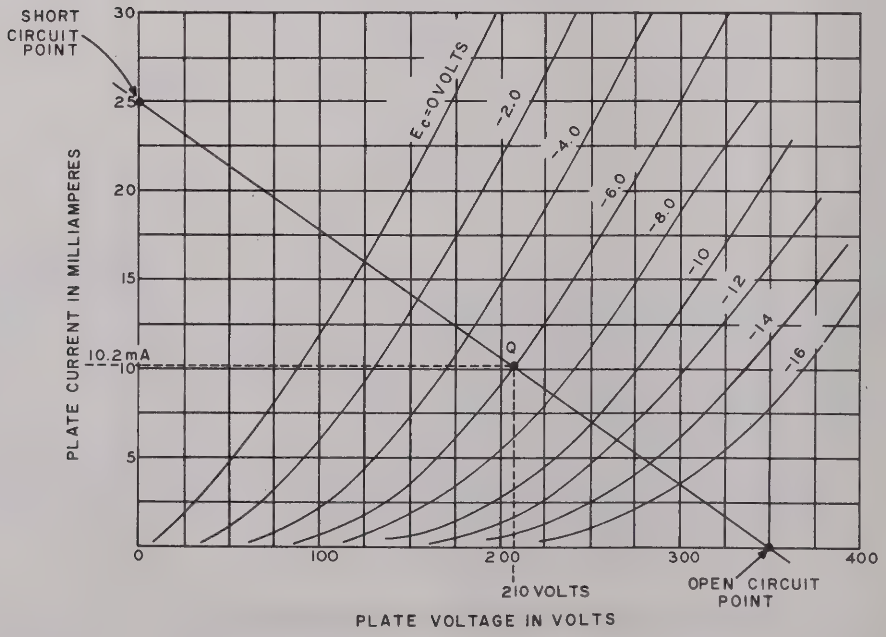


Figure 13

The other point for the load line can be found by assuming the opposite conditions. This is when V_1 is conducting so hard that E_b is zero and all of the plate supply voltage, E_{bb}, appears across R_L. Under these conditions, plate current is equal to $E_{bb} \div R_L$. In the circuit of Figure 12, the value of E_{bb} is 350 volts, and the value of R_L is 14 kΩ, making the maximum plate current 350 volts ÷ 14,000 ohms, or 25 mA. This set of conditions, $E_b = 0$ and $I_b = 25$ mA, forms the second point for the load line, the SHORT CIRCUIT POINT, as indicated in Figure 13. The load line is shown on the curves by drawing a straight line between these two points. By moving along the load line, the values of I_b and E_b for any value of E_c can be determined.

In Figure 12, the bias value, E_{cc}, is —6 volts. The intersection of the load line and the —6-volt E_c curve, marked Q in Figure 13, indicates the plate voltage and plate current. This is referred to as the **OPERATING POINT**, and it shows the tube voltage and current with only bias voltage applied to the grid. Dropping down from the load line to the plate voltage scale shows that the plate voltage is approximately 210 volts at the operating, or Q, point. Moving across the curves from the Q point to the plate current scale shows that the plate current is approximately 10.2 mA. Thus, you can quickly determine the value of plate voltage and plate current at any given values of grid voltage by just finding the intersection of the load line and the desired grid voltage curve. The open and short circuit points for the load line are summarized below:

OPEN CIRCUIT	SHORT CIRCUIT
$E_b = E_{bb}$	$E_b = 0$
$I_b = 0$	$I_b = E_{bb}/R_L$

The intersection of the load line and E_c curve shows the plate voltage and plate current at that particular value of E_c. The voltage across R_L is found by subtracting E_b from E_{bb}. In the form of an equation, E_{R_L} is equal to:

$$E_{R_L} = E_{bb} - E_b. \tag{8}$$

As an example, in Figure 12, when E_c equals —6 volts, E_b is equal to about 210 volts, as shown in Figure 13. The voltage drop across R_L is therefore:

$$E_{R_L} = 350 \text{ volts} - 210 \text{ volts}$$

$$= 140 \text{ volts.}$$

As the plate voltage, E_b, increases, the voltage drop across R_L (E_{R_L}) decreases, and as E_b decreases, E_{R_L} increases.

AMPLIFIER OPERATION

A primary purpose of a vacuum tube is to serve as an amplifier. The signal to be amplified is applied to the grid, and the output signal is developed across the plate load.

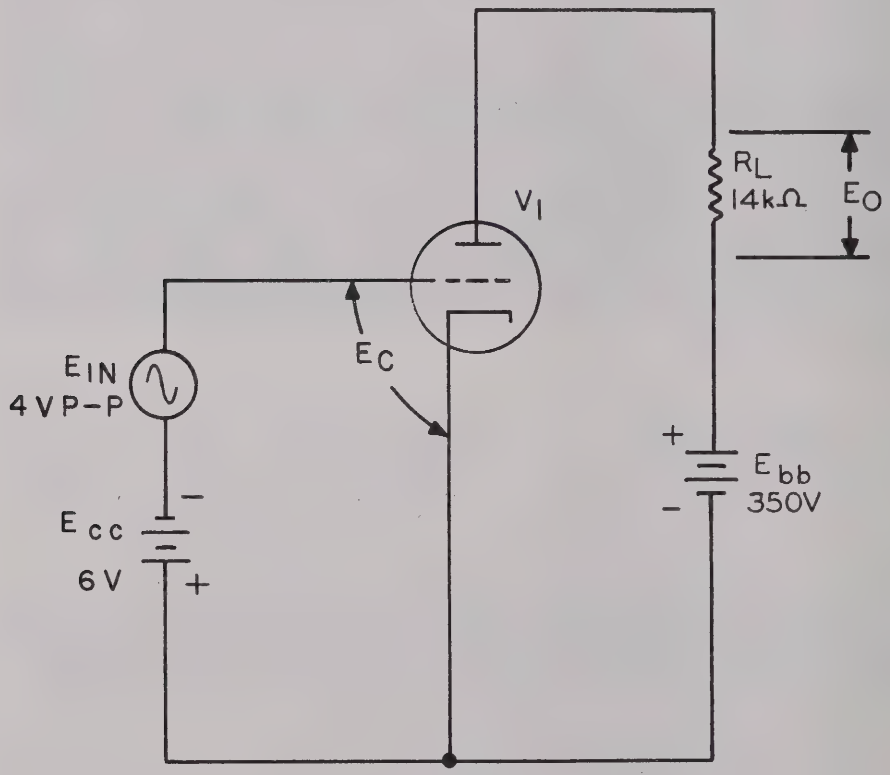


Figure 14

Figure 14 shows a simple amplifier circuit. The input signal, E_{IN}, is connected in series with the bias supply, E_{cc}. With E_{IN} equal to 4 volts peak-to-peak, the grid voltage E_c on V_1 will vary from —4 to —8 volts as the input signal swings from +2 to —2 volts. The load line can be used to determine the resultant voltage developed across load R_L, as well as the change in I_b and E_b.

Figure 15 shows the plate characteristic curves for V_1 of Figure 14 with the load line for the 14 kΩ resistor. Bias supply E_{cc} sets the operating point (Q point) for the tube. From Figure 15, $I_b = 10.2$ mA and $E_b = 210$ volts (approx.) at the operating point. As the input signal swings positive and negative, E_c decreases and increases. Let's consider the positive alternation first. With E_{IN} equal to +2 volts, E_c is equal to —6 volts plus 2 volts or —4 volts. Point A shows the intersection of the load line and the —4-volt E_c curve. Under these conditions, $I_b = 12$ mA and $E_b = 184$ volts. Therefore:

$$E_{R_L} = E_{bb} - E_b$$

$$= 350 - 184$$

$$= 166 \text{ volts.}$$

On the negative alternation of E_{IN}, E_c is equal to —6 volts plus —2 volts or —8 volts. Point B shows the intersection of the load line and the —8-volt E_c curve. Under these conditions, $I_b = 8.7$ mA, $E_b = 229$ volts and $E_{R_L} =$ 121 volts.

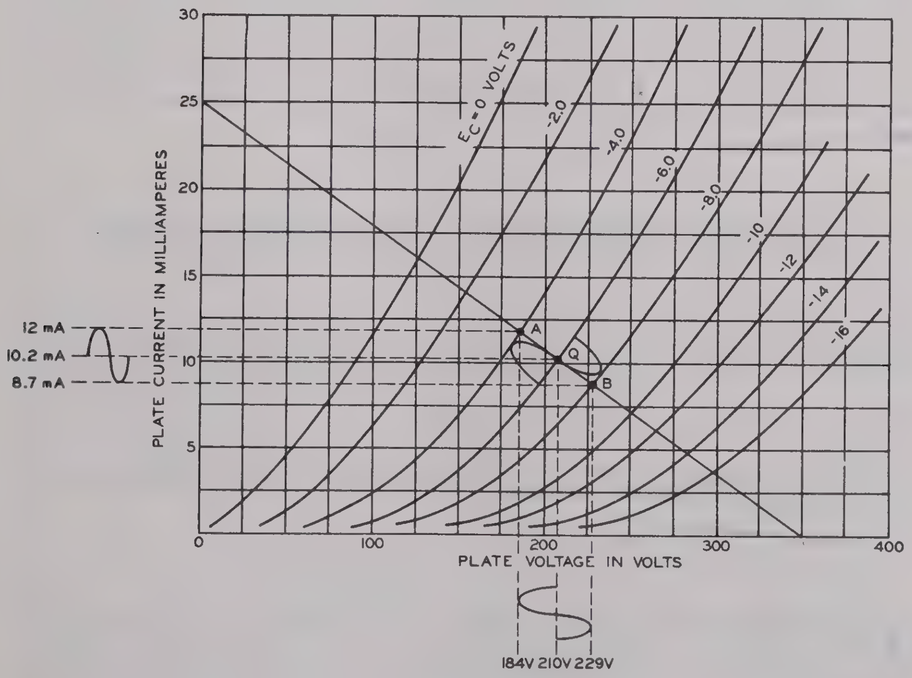


Figure 15

The values of I_b, E_b and E_{R_L} are tabulated for the various values of E_c below.

E_c	I_b	E_b	E_{R_L}
-4V	12 mA	184V	166V
-6V	10.2 mA	210V	140V
-8V	8.7 mA	229V	121V

Thus, as E_c varies from —4 to —8 volts, I_b varies from 12 to 8.7 mA, E_b varies from 184 to 229 volts and E_{R_L} varies from 166 to 121 volts. By using the characteristic curves and load line, you can determine exactly how a tube circuit operates. In this case, an input signal change of 4 volts causes the output signal to vary 45 volts.

Notice that the changes in I_b, E_b and E_{R_L} above and below the operating point values are not the same. For example, I_b increases 1.8 mA from 10.2 mA to 12 mA and decreases 1.5 mA from 10.2 mA to 8.7 mA. Likewise, E_b decreases 26 volts from 210 volts to 184 volts and increases 19 volts from 210 volts to 229 volts. This nonlinear change is due to the curvature of the tube's characteristics. By choosing the proper operating point and value of R_L, the nonlinear operation can be kept to a minimum.

DYNAMIC TRANSFER CHARACTERISTICS

Like the static plate families of Figures 3 and 4, the grid transfer family of Figure 7 does not show the effect of a load in the tube circuit. However, we can draw a line on the grid family graph which does show the effect of changes in grid voltage on plate current when the circuit contains a load resistance. A line of this type is called a **DYNAMIC TRANSFER CHARACTERISTIC CURVE.**

Like the load line, the dynamic transfer curve shows the effects of one load resistance only, and other curves must be drawn for other load resistances. Also, the transfer curve and the load line are both drawn with reference to some given value of plate supply voltage E_{bb}.

Since the dynamic transfer characteristic curve is not a straight line, it is necessary to plot more than two points to draw the curve accurately. Using the grid family of Figure 16, an E_{bb} value of 300 volts and a load resistance of 20,000 ohms as an example, we then select E_b values represented by the curves, and calculate the corresponding values of plate current.

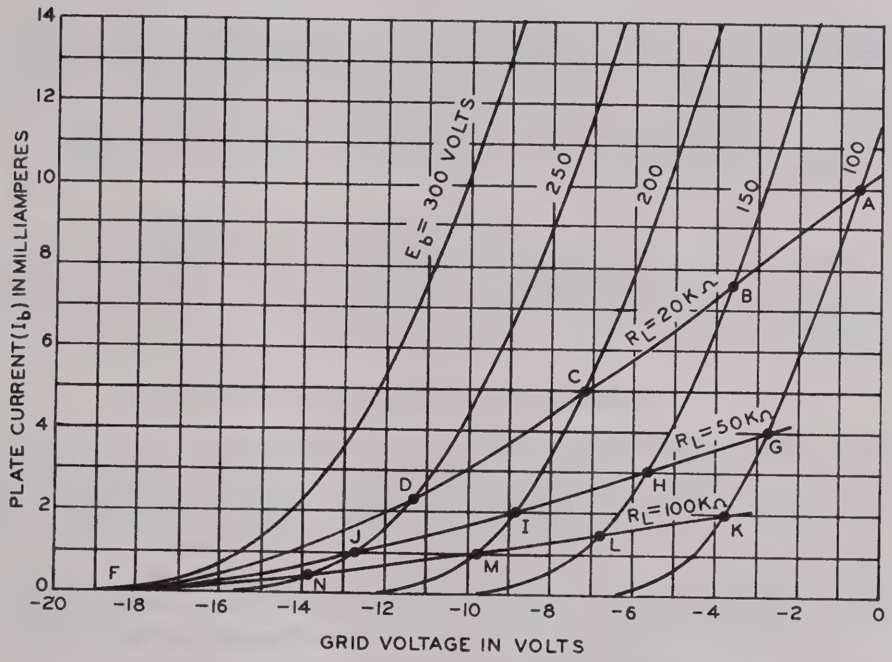


Figure 16

Choosing $E_b = 100$ volts (the curve farthest to the right), then $E_{R_L} = E_{bb} - E_b = 300 - 100$, or 200 volts. The load voltage, E_{R_L}, is equal to E_{bb} (here 300 volts) minus E_b. The plate current, I_b, is equal to E_{R_L}/R_L. Since R_L equals 20,000 ohms, $I_b = E_{R_L}/R_L = 200/20{,}000 = .01$ ampere, or 10 mA. Thus, the plate voltage of 100 volts and plate current of 10 mA give us point A on the curve in Figure 16.

Selecting a second plate voltage value, this time 150 volts (the next curve), $E_{R_L} = E_{bb} - E_b = 300 - 150 = 150$ volts. Therefore, $I_b = E_{R_L}/R_L = 150/20{,}000 = .0075$ ampere, or 7.5 mA. These values of E_b and I_b give us point B. When $E_b = 200$ volts, $I_b = (E_{bb} - E_b)/R_L = 100/20{,}000 = .005$ ampere, or 5 mA, for point C. When $E_b = 250$ volts, $I_b = 2.5$ mA for point D. Finally, when $E_b = E_{bb} = 300$ volts, $E_{R_L} = 0$, and $I_b = 0$ for point F. A line drawn joining points A, B, C, D and F forms the dynamic transfer characteristic curve for a 20,000 load resistance.

We can use the E_b values given by the grid curves to compute corresponding I_b values when the load resistance has other values. Thus, points G, H, I, J and F form the points needed to plot the dynamic curve when $R_L = 50,000$ ohms, while points K, L, M, N and F are the points when $R_L = 100,000$ ohms. The more points, the more accurate the curves.

The indicated R_L values show that the slopes of the transfer curves decrease as the resistance of the load becomes greater. Unlike the perfectly straight load line in Figure 15, the dynamic transfer curves of Figure 16 are somewhat curved. Comparing the three curves in Figure 16, we find that the curve for the highest load resistance has the least curvature.

Assume that the curves in Figure 16 apply to triode V_1 in Figure 11 and E_{cc} is a source of variable negative grid voltage and E_{bb} is equal to 300 volts. When R_L is equal to 50,000 ohms, its effects on the circuit are as shown in Figure 16.

Thus, when the grid voltage is equal to —4 volts, the plate current produced in the circuit is shown by the intersection of the $E_c = -4$ volts vertical line with the $R_L = 50,000$ ohms curve. Moving horizontally to the left from this point, we find that the plate current is equal to about 3.6 mA. When the grid voltage increases to —12 volts, the $R_L = 50,000$ ohms curve intersects the vertical line for $E_c = 12$ volts at a level indicating a plate current of about 1.2 mA. Unlike the load line in Figure 15, the dynamic transfer curves in Figure 16 do not directly indicate the plate voltage for a given grid voltage.

For operation with minimum distortion, it is necessary to operate an amplifier in a grid voltage-plate current region where equal changes of grid voltage result in the most nearly equal changes in plate current. This condition is easier to see with the dynamic transfer curves of Figure 16 than with the load lines of Figure 15. Curves of this kind are commonly used to study the behavior of the plate current when a varying voltage is applied to the grid. The input signal on the grid and the resultant plate current are then plotted along the characteristic curve.

The following Practice Exercise questions cover the subjects which you have just studied. They are:

TUBE FACTORS

RELATIONSHIP BETWEEN μ, g_m and r_p

LOAD RESISTOR

LOAD LINES

PLOTTING A LOAD LINE

AMPLIFIER OPERATION

DYNAMIC TRANSFER CHARACTERISTICS

31. The amplification factor of a tube is equal to the transconductance multiplied by the plate resistance. True or False?

32. If you place a load in the output circuit of a tube, does the grid have more or less effect on plate current than when a load is not present?

33. In the circuit of Figure 11, the plate current increases as you decrease the negative grid voltage. You should also expect (a) E_{R_L} and E_b to increase, (b) E_{R_L} to increase and E_b to decrease, (c) E_{R_L} to decrease and E_b to increase.

34. What does a load line show with regard to plate supply voltage E_{bb}, the load, and the tube?

35. Suppose that the value of E_{bb} in Figure 12 is increased to 400 volts and R_L is increased to 20 kΩ. Does the slope of the load line increase or decrease?

36. Using the values of E_{bb} and R_L in Exercise 35, what are the values of E_b and I_b at the open and short circuit points?

37. Suppose that E_c is equal to —8 volts in Figure 13. What is the value of E_b and E_{R_L}?

38. **How does E_{R_L} vary with respect to E_b?**

39. **Suppose that the input signal in Figure 14 is decreased to 3 volts peak-to-peak. Does the operating point change?**

40. **Examining the curves of Figure 15, is the change in E_b symmetrical?**

41. **With a dynamic transfer curve, the region where equal changes of control grid voltage produce the most nearly equal changes of plate current is harder to see than with a load line. True or False?**

SUMMARY

The ways in which vacuum tubes behave under different sets of conditions can be shown by charts called characteristic curves. Two common types of characteristic curves are the plate characteristic curves and the grid transfer curves. The plate characteristic curve shows how plate current varies with plate voltage for a given grid bias. The grid transfer characteristic curve shows how plate current varies with control grid voltage at a given plate voltage. Several curves of a given type on the same graph are called a family of curves. The family provides more information about a tube than a single curve does.

For best amplification, the control grid should have complete control of the plate current. The screen grid prevents changes of plate voltage from affecting the plate current. The pentode and the beam power tube prevent the screen grid from collecting secondary electrons emitted by the plate. In these tubes, screen current is small, and plate current is large.

The amplification factor is the ratio of the small plate voltage change to the small control grid voltage change that maintains the same plate current. Transconductance is the ratio of a small plate current change to the grid voltage change that produces it, with a constant plate voltage. Plate resistance, r_p, is the ratio of a small change in plate voltage to the resulting change in plate current with a constant grid voltage. The amplification factor is equal numerically to the product of the transconductance and the plate resistance.

A load resistance added to a tube circuit causes the control grid voltage to have less effect on plate current, and causes the plate voltage to change when the grid voltage changes the plate current. The load line shows the changes in the division of the plate supply voltage across the tube and the load when a change of grid voltage varies the plate current. A dynamic transfer characteristic shows how plate current changes with grid voltage when the tube circuit contains a load. The operating point is the point set by the control grid bias about which grid voltage, plate current and plate voltage vary. It is one of the factors that determine the operating region of the tube.

IMPORTANT DEFINITIONS

AC PLATE RESISTANCE — See DYNAMIC PLATE RESISTANCE.

AMPLIFICATION FACTOR (μ) — The ratio of a small change of plate voltage to the change of control grid voltage needed to maintain the same plate current.

CUTOFF GRID BIAS — The control grid bias at the point where plate current is reduced to zero.

DC PLATE RESISTANCE — See STATIC PLATE RESISTANCE.

DYNAMIC CHARACTERISTIC CURVE — A characteristic curve that shows the operation of a tube in a specific circuit.

DYNAMIC PLATE RESISTANCE (r_p) — The ratio of a small change in plate voltage to the resulting change in plate current, with the grid voltage held constant. Also called AC PLATE RESISTANCE.

DYNAMIC TRANSFER CHARACTERISTIC CURVE — A curve that shows how the load affects the change of plate current when the control grid voltage changes.

FAMILY OF CURVES — A group of curves of a given type on one graph.

LOAD LINE — A line drawn across a plate characteristic family that shows the changes in the division of the plate supply voltage between the load and the tube, and the changes in plate current caused by changes of control grid voltage.

MHO — The basic unit of conductance. This same unit is also called SIEMENS. In expressing transconductance of a tube, the micromho (10^{-6} mho) is commonly used.

MUTUAL CONDUCTANCE — See TRANSCONDUCTANCE.

OPERATING POINT — A point on a dynamic transfer curve, or on a load line, about which the grid voltage, plate current and plate voltage vary.

PLATE CHARACTERISTIC CURVE — A curve that shows the variation of plate current with plate voltage in a given tube.

PLATE CURRENT-CONTROL GRID VOLTAGE (I_b-E_c) CHARACTERISTIC CURVE — A curve that shows how changes of control grid voltage change plate current.

IMPORTANT DEFINITIONS (Continued)

STATIC CHARACTERISTIC CURVE — A characteristic curve that shows the operation of a tube only, without regard to the effects of other components.

STATIC PLATE RESISTANCE (r_b) — The ratio of a given dc plate voltage to the resulting dc plate current at a given dc grid bias. Also called DC PLATE RESISTANCE.

TRANSCONDUCTANCE (g_m) — The ratio of the change of plate current to the change of grid voltage causing it, with the plate voltage remaining constant. Also called MUTUAL CONDUCTANCE.

ESSENTIAL SYMBOLS AND EQUATIONS

E_{bb}	Plate supply voltage (volts)
E_b	Plate voltage (volts)
E_{cc}	Grid supply voltage (volts)
E_c	Grid voltage (volts)
g_m	Transconductance (mhos)
I_b	Plate current (amperes)
r_b	DC plate resistance (ohms)
r_p	AC plate resistance (ohms)
Δ	Small change of
μ	Amplification factor

$$\mu = \frac{\Delta E_b}{\Delta E_c} \text{ with } I_b \text{ constant} \tag{1}$$

$$g_m = \frac{\Delta I_b}{\Delta E_c} \text{ with } E_b \text{ constant} \tag{2}$$

$$r_p = \frac{\Delta E_b}{\Delta I_b} \text{ with } E_c \text{ constant} \tag{3}$$

$$r_b = \frac{E_b}{I_b} \tag{4}$$

$$\mu = g_m \times r_p \tag{5}$$

$$g_m = \frac{\mu}{r_p} \tag{6}$$

$$r_p = \frac{\mu}{g_m} \tag{7}$$

$$E_{R_L} = E_{bb} - E_b \tag{8}$$

PRACTICE EXERCISE SOLUTIONS

1. The static characteristic curve shows the operation of the tube only, without regard to other circuit components. The dynamic characteristic curve shows the operation of the tube in a specific circuit.

2. (a) plate characteristic curve.

3. (b) 3 mA. — From the plate voltage scale, move upward vertically along the 100-volt line to the curve, and then horizontally left to the plate current scale. The plate current is about 3 mA.

4. (a) increase.

5. (b) 1.0 mA. — Moving upward from 65 volts on the E_b scale to the curve, and to the left to the I_b scale, the plate current equals about 1.0 mA.

6. False — The curvature shows that the change of I_b with E_b is not linear. A linear curve on this graph would be a straight line.

7. A family of plate curves gives the variations of I_b with E_b for a number of grid bias voltages.

8. (a) more negative. — An E_b of 100 volts produces a plate current of 7 mA when $E_c = -2$ volts, but 220 volts is needed on the plate to produce this same current when $E_c = -8$ volts.

9. (b) less negative. — For example, when $E_b = 200$ volts, I_b is 10 mA with -6 volts on the grid, and increases to 20 mA when E_c is reduced -4 volts.

10. (c) change by a large amount. — This is typical in triode tubes.

11. (a) only slightly. — The plate voltage then does not greatly oppose the action of the grid voltage.

12. (a) screen grid.

13. True — The shielding effect of the screen prevents E_b from greatly affecting I_b.

14. (b) small.

15. About 8.1 mA.

16. 4 mA.

PRACTICE EXERCISE SOLUTIONS (Continued)

17. (a) less negative.

18. Cutoff grid bias.

19. (c) considerably more effect on plate current.

20. grid; plate

21. (b) amplification factor.

22. Plate current is held constant when determining μ.

23. 32.5 — $\mu = \frac{\Delta E_b}{\Delta E_c} = \frac{65 \text{ volts}}{2 \text{ volts}} = 32.5$

24. No — The value of μ will vary, depending upon the point where it is determined.

25. (a) transconductance.

26. (c) micromhos. — Although the basic unit of transconductance is the mho, it is too large and the micromho is commonly used.

27. 25,000 micromhos. — $g_m = \frac{\Delta I_b}{\Delta E_c} = \frac{25 \times 10^{-3} \text{ amperes}}{1 \text{ volt}} = 25 \times 10^{-3}$ mhos or 25,000 micromhos.

28. (b) $\Delta E_b / \Delta I_b$.

29. The ohm is the basic unit of measurement for dynamic plate resistance.

30. 3.5 kΩ. — $r_p = \frac{\Delta E_b}{\Delta I_b} = \frac{35 \text{ volts}}{10 \times 10^{-3} \text{ amperes}} = 3.5 \times 10^3$ ohms $= 3.5$ kΩ.

31. True — $\mu = g_m r_p$.

32. The grid has less effect on plate current when a load is present.

33. (b) E_{R_L} to increase and E_b to decrease. — With E_c smaller, the resistance of V_1 is less. Therefore, the voltage division changes to make E_b less and E_{R_L} greater.

PRACTICE EXERCISE SOLUTIONS (Continued)

34. The load line shows the division of E_{bb} between the load and the tube.

35. With R_L equal to 20 kΩ and E_{bb} equal to 400 volts, the short circuit I_b would be 20 mA. This would place the load line below that in Figure 13, decreasing the slope.

36. Open circuit: $I_b = 0$ mA and $E_b = E_{bb} = 400$ volts;
short circuit: $I_b = E_{bb}/R_L = 400/20K = 20$ mA and $E_b = 0$ volts.

37. $E_b =$ approximately 230 volts and $E_{R_L} = E_{bb} - E_b = 350 - 230 = 120$ volts.

38. As E_b increases, E_{R_L} decreases, and as E_b decreases, E_{R_L} increases ($E_{R_L} = E_{bb} - E_b$).

39. No — The operating point is fixed by the value of E_c, R_L and E_{bb}. As long as these remain constant, the operating point does not change.

40. No — The change in E_b is not symmetrical. E_b increases 26 volts in going from 140 to 166 volts but decreases only 19 volts in going from 140 to 121 volts.

41. False — This region is easier to see with a dynamic transfer curve than it is with a load line.

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ONE OF THE
BELL & HOWELL SCHOOLS

1052A
EXAMINATION CHECK SHEET

1052A

1. A - A PLATE CHARACTERISTIC CURVE SHOWS PLATE CURRENT VALUES CORRESPONDING TO VARIOUS VALUES OF -- PLATE VOLTAGE.
The grid voltage is held constant while plate voltage is varied to obtain the plate characteristic curve.

2. D - THE CHANGES IN PLATE CURRENT PRODUCED BY VARYING BOTH THE PLATE VOLTAGE AND THE GRID VOLTAGE ARE SHOWN BY A -- FAMILY OF PLATE CURVES.
In the family of plate curves, changes in plate current caused by varying plate voltage are plotted for various values of grid voltage.

3. A - THE PLATE CURVES OF A PENTODE SHOW THAT -- I_b IS RELATIVELY CONSTANT AS E_b VARIES.
The screen grid in a tetrode and a pentode makes plate current relatively independent of plate voltage.

4. B - FOR GREATEST VOLTAGE AMPLIFICAT THE PLATE CURRENT OF A TUBE SHOULD BE CONTROLLED MAINLY BY THE -- CONTROL GRID.
In a tetrode or pentode, the screen grid makes the current independent of plate voltage. This illustrates why the gain of a tetrode or pentode is higher than that of a triode.

5. A - A NUMBER THAT TELLS US HOW MANY TIMES MORE EFFECTIVE THE GRID IS THAN THE PLATE IN CONTROLLING PLATE CURRENT IS THE -- AMPLIFICATION FACTOR.
The amplification factor (μ) is equal to a change in plate voltage divided by the change in grid voltage that caused it with plate current held constant.

6. C - WHAT IS THE TRANSCONDUCTANCE OF A TUBE IF A CHANGE IN GRID VOLTAGE OF 2 VOLTS CAUSES A 15 mA CHANGE IN PLATE CURRENT? -- 7500 µMHOS.
Transconductance, g_m, is equal to

$$g_m = \frac{\Delta I_b}{\Delta E_c} \quad \frac{15 \times 10^{-3} \text{ amperes}}{2 \text{ volts}} = 7.5 \times 10^{-3} \text{ mhos} = 7500 \ \mu\text{mhos}.$$

7. B - WHAT IS THE AC PLATE RESISTANCE OF A TUBE IN WHICH A 240 VOLT CHANGE IN PLATE VOLTAGE CAUSES THE PLATE CURRENT TO CHANGE BY 0.8 mA, WITH THE GRID VOLTAGE REMAINING CONSTANT? -- 300,000 OHMS.
Dynamic plate resistance, r_p, is equal to

$$r_p = \frac{\Delta E_b}{\Delta I_b} = \frac{240 \text{ volts}}{.8 \text{ mA}} = 300{,}000 \text{ ohms}$$

8. D - WHAT IS THE VALUE OF μ IF $g_m = 2500$ µMHOS AND $r_p = 25$K OHMS? -- 62.5.
In terms of g_m and r_p, μ is equal to:

$$\mu = g_m r_p = 2500 \times 10^{-6} \text{ mhos} \times 25 \times 10^3 \text{ ohms} = 62.5$$

9. A - SUPPOSE $R_L = 47$K OHMS, $E_{bb} = 350$ VOLTS AND $I_b = 5$ mA. WHAT IS THE VALUE OF E_{R_L}? -- 235 VOLTS.
The value of E_{R_L} is equal to

$$E_{R_L} = I_b R_L = 5 \times 10^{-3} \text{ amperes} \times 47 \times 10^3 \text{ ohms} = 235 \text{ volts.}$$

10. C - WHAT IS THE OPEN CIRCUIT I_b AND E_b FOR A LOAD LINE WHEN $E_{bb} = 300$ VOLTS AND $R_L = 15$K OHMS? -- $E_b = 300$ VOLTS AND $I_b = 0$.
The open circuit point is always $I_b = 0$ and $E_b = E_{bb}$.

QUESTIONS

IMPORTANT — These instructions **MUST** be accurately followed to avoid loss, or errors in grading.

Indicate your answer on this sheet by filling in the box for the most correct answer to each question, as illustrated in the example below.

When all questions have been answered, place the answer card in the proper position to line up the boxes on the card with the boxes on the sheet.

Next, copy the complete lesson code into the space provided on the card, and fill in the answer boxes to correspond with those previously filled in on this sheet.

Before mailing, be certain your correct student number, name and address appear on the card.

LESSON CODE
1052A

Example: A fish commonly found in home aquariums is the
A ■ B ☐ C ☐ D ☐
A. gold fish. B. shark. C. barracuda. D. whale.

1. A ☒ B ☐ C ☐ D ☐
A plate characteristic curve shows plate current values corresponding to various values of
(A) plate voltage. (B) grid current. (C) cathode voltage. (D) temperature.

2. A ☐ B ☐ C ☐ D ☒
The changes in plate current produced by varying both the plate voltage and the grid voltage are shown by a
(A) single grid transfer curve. (B) single plate characteristic curve. (C) transconductance curve. (D) family of plate curves.

3. A ☒ B ☐ C ☐ D ☐
The plate curves of a pentode show that
(A) I_b is relatively constant as E_b varies. (B) E_b is relatively constant as I_b varies. (C) I_b is relatively constant as E_c varies. (D) I_b is directly proportional to E_c.

4. A ☐ B ☒ C ☐ D ☐
For greatest voltage amplification, the plate current of a tube should be controlled mainly by the
(A) plate. (B) control grid. (C) cathode. (D) screen grid.

5. A ☒ B ☐ C ☐ D ☐
A number that tells us how many times more effective the grid is than the plate in controlling plate current is the
(A) amplification factor. (B) dc plate resistance. (C) transfer characteristic. (D) plate efficiency.

6. A ☐ B ☐ C ☒ D ☐
What is the transconductance of a tube if a change in grid voltage of 2 volts causes a 15-mA change in plate current?
(A) 7500 mhos. (B) 3000 μmhos. (C) 7500 μmhos. (D) 1500 μmhos.

7. A ☐ B ☒ C ☐ D ☐
What is the ac plate resistance of a tube in which a 240-volt change in plate voltage causes the plate current to change by 0.8 mA, with the grid voltage remaining constant?
(A) 192 ohms. (B) 300,000 ohms. (C) 240 ohms. (D) .0008 ohm.

8. A ☐ B ☐ C ☐ D ☒
What is the value of μ if $g_m = 2500$ μmhos and $r_p = 25$ kΩ?
(A) 24 (B) 250 (C) 625 (D) 62.5

9. A ☒ B ☐ C ☐ D ☐
Suppose $R_L = 47$ kΩ, $E_{bb} = 350$ volts and $I_b = 5$ mA. What is the value of E_{R_L}?
(A) 235 volts. (B) 315 volts. (C) 225 volts. (D) 177 volts.

10. A ☐ B ☐ C ☒ D ☐
What is the open circuit I_b and E_b for a load line when $E_{bb} = 300$ volts and $R_L = 15$ kΩ?
(A) $E_b = 0$ and $I_b = 20$ mA. (B) $E_b = 300$ volts and $I_b = 20$ mA. (C) $E_b = 300$ volts and $I_b = 0$. (D) $E_b = 250$ volts and $I_b = 10$ mA.

47
5
235

EXPERIMENT 4

VACUUM TUBE CIRCUITS— COMMON-CATHODE AMPLIFIER

PARTS NEEDED

- 1 - Multimeter with Test Leads and Spring Adapters
- 1 - Partially-Completed Design Console
- 16 - Modular Connectors
- 1 - 4.7 kΩ, 1/2 W, Resistor
- 1 - 100 kΩ, 1/2 W, Resistor
- 1 - 220 kΩ, 1/2 W, Resistor
- 1 - 470 kΩ, 1/2 W, Resistor
- 1 - 10 μF, 50V, Electrolytic Capacitor
- 1 - 12AU7 Vacuum Tube
- 1 - 9-Pin Tube Socket with Leads
- - No. 22 Solid Hookup Wire

OBJECTIVE

In this experiment you will set up a common-cathode type vacuum tube amplifier circuit, and analyze the voltage gain characteristics. The measured voltage gain will be compared with the μ of the tube. The effects of a cathode bypass capacitor will also be examined.

PROCEDURE

1. Connect the circuit of Figure 4-1, following the layout of Figure 4-2. (Connecting the circuit includes the insertion of the tube.) Make sure that the design console is turned off while constructing or changing the circuit. Do not connect the jumper wire at this time. Again, exercise care because of the high voltages.

2. Turn on the design console. Since the low voltage regulated supply is not used in this circuit, set its voltage adjust control fully counterclockwise.

3. This circuit is a conventional common-cathode amplifier circuit. We will apply a 60 Hz test signal to the grid circuit, and measure the input and output signal amplitudes to determine the voltage gain.

Using the multimeter, measure the voltages at the grid, cathode, and plate, and record below. Remember, all measurements are to be made with respect to ground (GND). Use caution since high voltages, +180 volts, are present in the circuit.

Cathode - 5 volts dc

Grid - 0 volts dc

Plate - 98 volts dc

Note that the grid-to-ground dc voltage is zero. However, the bias is measured between grid and cathode. Thus, the grid-to-cathode voltage will be the same as the cathode-to-ground voltage.

4. Turn off the Design Console, and connect the jumper wire in Figure 4-2. This applies a 60 Hz test signal to the grid circuit of V_1. Turn on the Design Console.

5. Using the output function on your multimeter, measure the ac voltage at the grid of V_1 and record below. The output function of the meter internally connects a blocking capacitor, so ac voltages can be measured in the presence of dc voltages. You should measure about 2 volts ac (rms).

AC Grid Voltage = 2 volts ac

6. Now measure the ac signal voltage at the plate of V_1, using the output function. This will be greater than 10 volts ac. Be careful, since a high dc voltage is present on the plate and on R_1. You should measure about 30 volts ac (rms).

AC Plate Voltage = 37 volts

7. The voltage gain of the stage is equal to the output voltage (at the plate), divided by the input voltage (at the grid). Perform this calculation, and record the gain below.

$$\text{Voltage Gain} = \frac{\text{AC Plate Voltage}}{\text{AC Grid Voltage}} = \frac{37}{2} = 18.5$$

8. The voltage gain of a practical amplifier circuit is always less than the μ of the tube. Since a 12AU7 has a published μ of about 20, you should obtain a gain of about 15.

The voltage gain of a common-cathode stage can also be calculated by the formula shown below:

$$\text{Voltage Gain } (A_V) = \frac{\mu R_L}{R_L + r_p}$$

Using the value of R_1 from the circuit for R_L, (100 kΩ) and assuming a μ of 20 and an r_p of 6 kΩ (published typical data), calculate the voltage gain of the circuit and record below.

$$\frac{20\,(100k)}{100k + 6k} = \frac{2000}{106}$$

18.7
106)2000
[illegible]

Calculated A_V 18.7

Your calculated gain should compare favorably with the measured gain. Any differences can be attributed to a slightly different value of μ or r_p for the particular tube that you are using. Also, the cathode bias resistor R_2 is unbypassed in this circuit, and the resultant voltage across R_2 reduces gain (to a maximum of 20, according to the published "average characteristics").

9. To show the effects of the addition of a cathode bypass capacitor, turn off the design console and connect a 10 μF, 50 volt, electrolytic in parallel with the 4.7 kΩ cathode resistor. The + end of the capacitor connects to the cathode end of the 4.7 kΩ resistor.

10. Turn on the design console, and measure the ac grid voltage and ac plate voltage. Compute the circuit voltage gain. Be sure to use the output function of the multimeter.

AC Grid Voltage = 2 volts ac

AC Plate Voltage = 60 volts ac

Voltage Gain 30

Your measured ac plate voltage and calculated gain should be higher than when R_2 was not bypassed. The bypass capacitor greatly reduces the impedance from cathode to ground, thus greatly reducing the degeneration and increasing the gain. However, the voltage gain should still be less than 20. Parts tolerances, equipment and slight meter reading errors may cause the voltage gain to calculate out to more than 20. Also, the tube may actually have a higher gain than is indicated by its "average characteristics." Turn off the design console.

CONCLUSION

The common-cathode vacuum tube amplifier provides a high voltage gain, with the circuit voltage gain always less than the μ of the tube. When the cathode bypass capacitor is not used to bypass the cathode bias resistor, the degeneration (or negative feedback) developed causes the circuit to have a lower voltage gain than when a bypass capacitor is used. The advantages of negative feedback include wider frequency response and reduced distortion.

NOTES

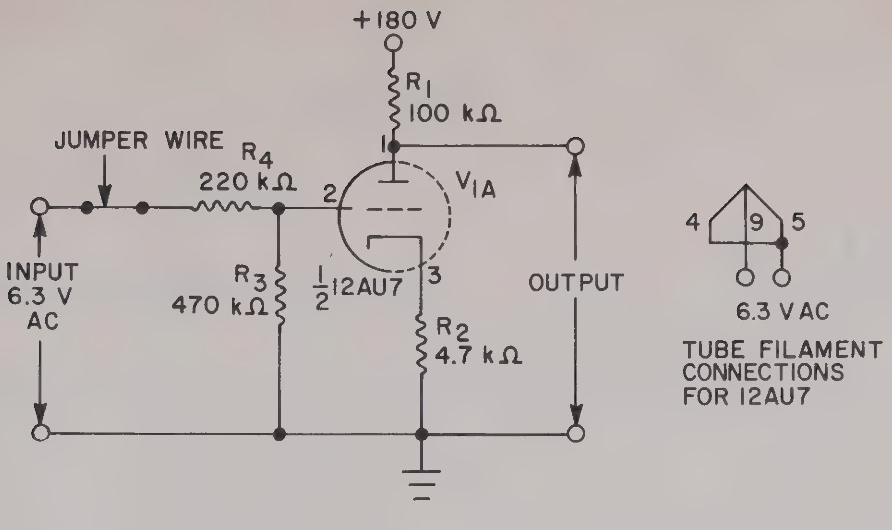

FIGURE 4-1

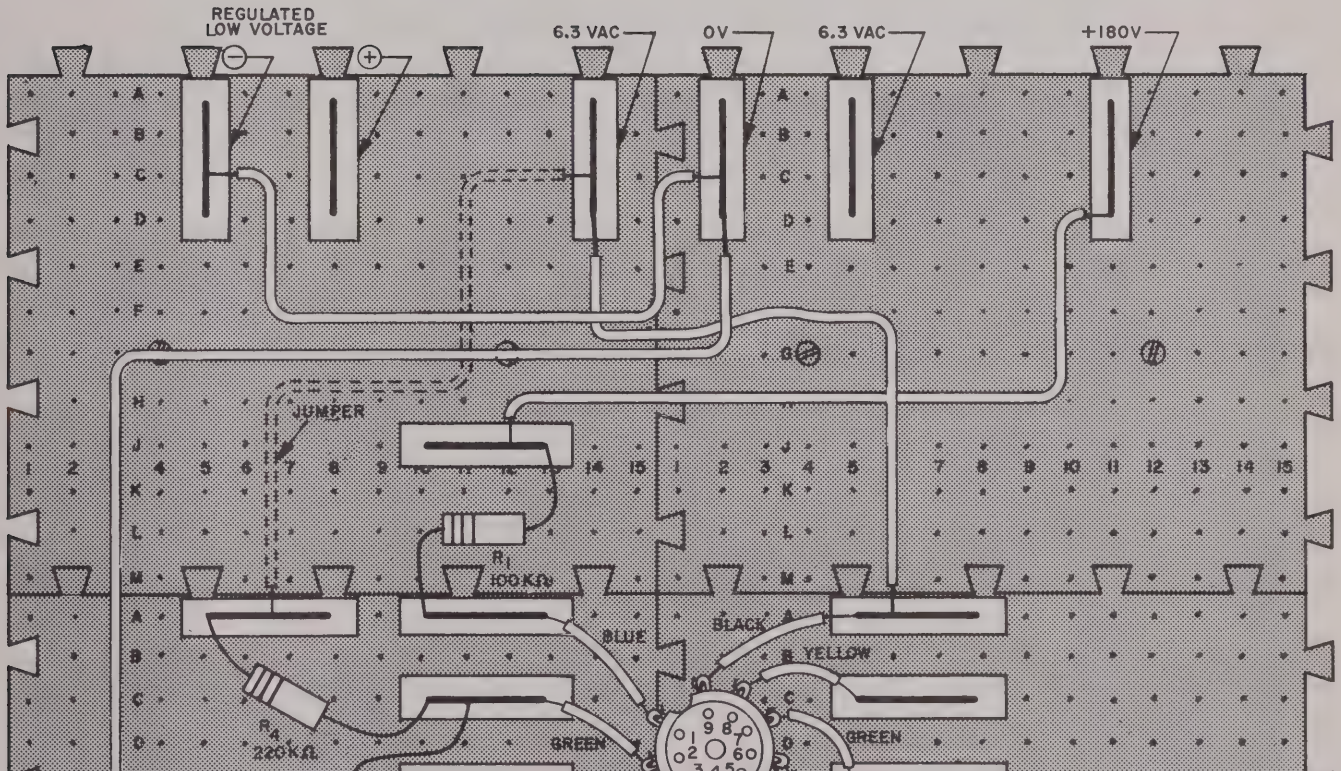

FIGURE 4-2

NOTES

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9504-4A
EXAMINATION CHECK SHEET

1. C - THE CIRCUIT OF FIGURE 4-1 IS REFERRED TO AS A -- COMMON-CATHODE AMPLIFIER.
Since the cathode circuit is common to both input and output circuits, the arrangement is referred to as a common-cathode amplifier.

2. C - WHAT IS THE PURPOSE OF R_2 IN THE CIRCUIT OF FIGURE 4-1? -- CATHODE BIAS.
Plate current flowing through R_2 develops the cathode bias.

3. B - IN THE CIRCUIT OF FIGURE 4-1, THE VOLTAGE GAIN IS -- LESS THAN THE μ OF THE TUBE.
The voltage gain of a common-cathode amplifier is always less than the μ of the tube.

4. D - WHEN A CATHODE BYPASS CAPACITOR IS CONNECTED ACROSS R_2, -- THE CIRCUIT VOLTAGE GAIN INCREASES.
The addition of the cathode bias capacitor greatly reduces degeneration, thus increasing voltage gain.

5. A - SUPPOSE THAT, IN THE CIRCUIT OF FIGURE 4-1, V_1 HAS A μ OF 50, r_p IS 7 kΩ AND R_L IS 100 kΩ. WHAT IS THE VOLTAGE GAIN? ASSUME THAT R_2 IS BYPASSED, AS IN STEP 9. -- 47
The voltage gain of the circuit is found as shown below:

$$A_V = \frac{\mu R_L}{R_L + r_p} = \frac{50 \times 100}{100 + 7} = \frac{5000}{107} = 47 \text{ (approximately).}$$

UNIT EXAMINATION FOR

COURSE 125

This examination contains a number of different type questions: multiple choice, true or false, fill in the blank and direct question. To assist us in grading, please print your answers clearly on the answer sheet. **COMPLETE THE PORTION STATING YOUR NAME, ADDRESS AND STUDENT NUMBER ON THE ANSWER SHEET AND SEND ONLY THE ANSWER SHEET FOR GRADING.** Retain the examination questions for your records.

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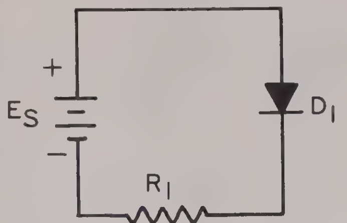
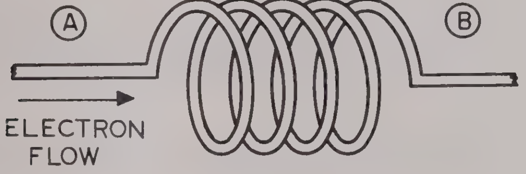
1. The diode shown in the circuit below is forward biased. [✓ True] or False?



2. In a diode vacuum tube do electrons flow from [✓ cathode to anode] or anode to cathode? ________________

3. The basic law of magnetic poles states that, like poles repel.

4. With electron flow in the direction of the arrow shown in the diagram below, point A is the north magnetic pole.



5. What is the peak value of a sinusoidal ac voltage with a 150-volt rms rating? [illegible]

6. What is the rms voltage rating of a sinusoidal ac voltage that has a peak-to-peak value of 300 volts? 106 V rms

7. If the primary current of a transformer is 1.5 amperes and the secondary current is 10 amperes, what is the turns ratio? 3:20

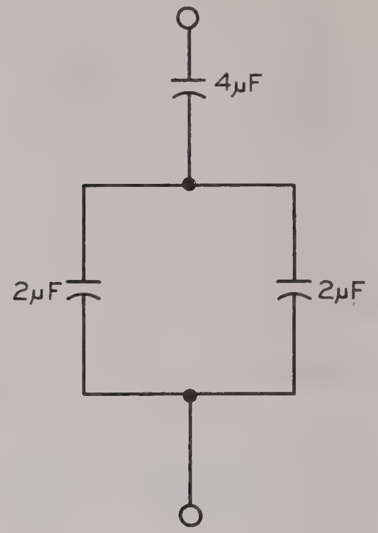
8. The basic unit of inductance is the henry.

14,14
15
7070
1414
21210

150

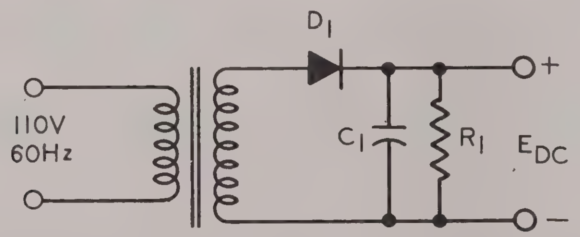
7.07
15
3535
707
10605

9. What is the total value of capacity in the circuit shown below? 2 μF



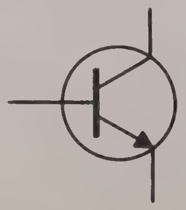
10. What is the accumulated charge in coulombs on a .5 μF capacitor if the voltage across the capacitor is 100 volts? 5×10^{-5} coul.

11. In the power supply circuit shown below does C_1 discharge through the load when D_1 is conducting or cut off? cut off



12. To obtain good power supply regulation, the internal resistance of the power supply should be lower.

13. The schematic symbol shown below is that of a PNP transistor. True or [✓ False]?



14. For normal transistor operation, the collector junction is reversed biased.

15. In a transistor, collector current is approximately proportional to base current. [✓ True] or False?

16. In a common-emitter amplifier circuit, if a base current change of 150 μA produces a collector current change of 4.5 milliamperes, h_{fe} equals 30.

$$\frac{4.5 \times 10^{-3}}{1.5 \times 10^{-4}}$$

17. As the grid of a triode electron tube is made more negative with respect to the cathode, the plate current decreases.

18. The addition of a screen grid in a tetrode results in an increase in the grid to plate capacity. True or [✓ False?]

$$\frac{60}{1.5}$$

19. What is the amplification factor of a tube if a change in grid voltage of 1.5 volts causes a 60-volt change in plate voltage? 40

20. The plate characteristic curves of a tetrode show that plate current is relatively constant as plate voltage varies in the plate voltage range above the dip region. [✓ True] or False?

NOV 12 1976

UNIT EXAMINATION 125
ANSWER SHEET

GRADE 100

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Write your answers in the space provided. Be sure to include units, such as volts, μF, etc. where necessary. **RETURN ONLY THE ANSWER SHEET FOR GRADING.** Keep the exam for your records.

1. TRUE
2. cathode to anode
3. repel
4. north
5. 212 ~~volts~~ volts
6. 106 volts rms
7. 3:20
8. henry
9. 2 μf
10. 5×10^{-5} coul,
11. cut off
12. low
13. False
14. reverse
15. True
16. 30
17. decreases
18. False
19. 40
20. True